SOIL FERTILITY AND CORN AND SOYBEAN YIELD AND QUALITY IN A SIX-YEAR NITROGEN AND PHOSPHORUS FERTILIZATION EXPERIMENT

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ABSTRACT

Optimum management of nitrogen (N) and phosphorus (P) fertilizers for corn [*Zea mays* L.] and soybean [*Glycine max* (L.) Merr.] production requires quantitative understanding of multiple soil processes and crop responses, including supply and immobilization of N and P by soil, the response of yield and quality to nutrient availability, and the relationships and interactions between N and P cycling, crop response, and other soil physical and chemical variables.

We conducted a six-year experiment on two 16-ha fields on glacial-till soils in south-central Minnesota. In each year of a corn–soybean rotation, we measured soil physical and chemical parameters and grain yield and quality at a 0.014-ha resolution within each field. These observations coincided with placement of a randomized complete block, split plot design of N and P fertilizer treatments.

Spatial patterns of mineralizable N were consistent over time. Mineralizable N was highly correlated to soil nitrate at a well-drained site, but not at a poorly-drained site. Increases in available soil P per kg of net P addition were significantly related to soil pH.

Within fields, spatial patterns of soybean yields were highly correlated across years, and we observed consistent relationships between yield and soil variables. Overall, soybean yield related positively to soil P and Zn and negatively to pH at all site-years. Quadratic-plateau regression models of soybean yield in relation to soil P and Zn indicate that in high pH soils at these sites, yield is optimized when soil P and Zn levels are higher than current recommendations.

Corn yields responded significantly to N rate and N rate by P rate interaction in all site-years. Whole-field economic optimum N rate differed significantly by site-year and by P treatment at some site-years.

Site-specific P fertilization should account for spatial variation in soil P buffering capacity. Nitrogen mineralization and N×P nutrient interactions should be accounted for in agronomic management decisions for corn production. The consistent influence of soil pH on nutrient cycling and crop response indicates the potential benefit to amelioration of high pH in calcareous glacial-till soils. Results highlight the significance of spatial variability in nutrient cycling to crop management.

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GENERAL INTRODUCTION

The recent and rapid growth in the technological capacity to generate, process, and analyze quantitative geospatial information on crops and soils has created new opportunities to refine agronomic management. Rising prices for crops, fertilizer, and land have increased the economic incentive to optimize management for the soil and environmental conditions at each point within agricultural fields. By accurately and precisely tailoring agronomic inputs and production practices to the landscape, site-specific management practices have theoretical potential to enhance economic returns to farmers, to make more efficient use of scarce resources such as land, water, fuel, fertilizer, and labor, and to minimize environmental impacts associated with excessive fertilization or poor crop growth (Mallarino et al., 2001; Wolf and Nowak, 1995).

While technological capacity for site-specific management is widely available and adopted by farmers (Diekmann and Batte, 2010), the benefits that might accrue from site-specific agronomic management have remained largely theoretical. This is due to a lack of basic agronomic understanding of how to practice site-specific management. Agricultural scientists first explicitly studied the variability inherent in agricultural fields over 100 years ago (Mercer and Hall, 1911). However, for much of the past century farmers did not have capacity to manage different parts of fields in quantitatively different ways. Agronomic research focused on developing production recommendations that could be broadly applicable across states or larger regions. Technology for site-specific management became available only within the past 20 years. Over these years, substantial research investments have been made in site-specific management, including research on soil fertility (Lamb and Rehm, 2002), relationships between crop yield and soil parameters (Kaspar et al., 2004; Kravchenko and Bullock, 2002; Sawchik and Mallarino, 2008), and optimum nutrient rates for crop production (Barker and Sawyer, 2012; Lambert et al., 2006). Despite this considerable research effort, site-specific production recommendations have not been forthcoming (Martín et al., 2005). A dearth of prescriptive recommendations has been due, in part, to experimental designs aimed at providing descriptive, rather than prescriptive, information, as well as to failures to pursue interpretive approaches targeting spatial variation in crop response.

To realize the full potential of site-specific management capabilities, farmers require quantitative understanding of the relationship between soil properties, agronomic management, and crop yield and quality. To better understand these relationships and provide farmers and agronomists with improved guidance for site-specific management, we conducted a six-year experiment on two 16-ha field sites in south-central Minnesota. Fields at both sites were in a long-term corn [*Zea mays* L.]–soybean [*Glycine max* (L.) Merr.] rotation. Soils at both sites formed from calcareous glacial till typical of the Des Moines Lobe glacial region of the North-Central United States, which produces approximately 30% of the United States corn and soybean crops (USDA-NASS, 2012).

Specifically, the objectives of this work were to: (1) characterize the inherent variability in soil chemical properties in these fields (Chapter 2); (2) determine behavior of spatial patterns in soil nitrogen over time (Chapter 2); (3) determine response of soil phosphorus to fertilizer phosphorus additions and crop removals over time (Chapters 1 and 2); (4) characterize spatial variability in corn and soybean yield and quality (Chapters 3, 5, and 6); (5) relate corn and soybean yield and quality to soil chemical properties (Chapters 3, 5, and 6); (6) determine site-specific crop nutrient recommendations for corn and soybean yield (Chapters 3, 4, 5, and 6); and (7) investigate potential approaches to ameliorating yield-limiting soil chemical properties (Chapter 7).

CHAPTER 1: Corn and Soybean Grain Phosphorus Content Relationship with Soil Phosphorus, Phosphorus Fertilizer, and Crop Yield[1]

Abstract: Most fertilizer phosphorus (P) rate recommendations for the North-Central United States are based on combination of a critical soil test P value and a mass-balance calculation of fertilizer P required to maintain critical soil test P. Accurate estimates of grain P removal are an essential component of P mass-balance calculation. Current North-Central extension service guidelines recommend that estimates of corn and soybean grain P removal should be calculated using constant grain P concentrations. We reviewed research from the North-Central region to determine the extent to which variation in grain P concentration accounts for differences in crop P removal, and to determine whether predictions of grain P concentration can be improved through consideration of soil test P, crop yield, and fertilizer P application. We found that soil test P, grain yield, and fertilizer P are predictor variables that may significantly improve estimates of grain P concentration for corn and soybeans.

Introduction

Accurate estimation of corn and soybean crop phosphorus (P) removal is important to farmers and researchers as they work to improve P management in agricultural systems. Most P fertilizer rate recommendations for the North-Central United States are based on a combination of a critical soil test P (STP) value and a mass-balance calculation of the fertilizer P required to maintain the critical STP level (Gerwing and Gelderman, 2005; Mallarino, 2009; Rehm et al., 2001; Rehm et al., 2006; Sawyer et al., 2008; Vitosh et al., 1995). Grain P removal is an essential component of a mass-balance approach to P management. Accurate estimates of grain P removal improve the constraint of mass-balance calculations and help to avoid both under-application of fertilizer P and

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associated potential for yield loss, as well as over-application of P and associated potential for economic loss and environmental impact (Mallarino, 2009; Prater, 2007). A better-constrained P mass-balance can assist in identifying and quantifying non-fertilizer P sources (mineralization, desorption), sinks (immobilization, fixation), and fluxes (erosion, runoff, leaching). Published university extension service guidelines for the North-Central United States suggest constant grain P concentration (GPC) values for each crop type (Rehm, 2001; Sawyer et al., 2008; Vitosh et al., 1995). However, some authors have questioned the usefulness of average GPC values to estimate nutrient removal (Heckman et al., 2003).

Multiple lines of evidence suggest that constant GPC values may not be appropriate. Prater (2007) identified large variation in both corn and soybean GPC and suggested a need to understand factors that affect GPC to improve removal estimates. Several researchers have reported that the rate of fertilizer P application necessary to maintain STP at a given level is proportional to the STP value. At low STP values, low fertilizer P rates are needed to maintain STP; at high STP values, substantially higher fertilizer P rates are needed to maintain STP (Barber, 1979; Eghball et al., 2003; Randall et al., 1997; Webb et al., 1992). Two possible explanations have been provided for this phenomenon. The first explanation is that at higher STP values in soils with a history of P application, P buffering capacity is higher (Randall et al., 1997). The second explanation is that at higher STP values, crop P removal is higher, as crops respond to the higher STP level first with higher yield and then with excess uptake of P (Prater, 2007; Randall et al., 1997). This second explanation is most apparent in the work of Zhang et al. (1995), who reported poor correlation between total fertilizer P applications and increases in Mehlich III STP, but a linear relationship between the change in Mehlich III STP values and the net P addition (P fertilizer applied - grain P removal).

Although relatively few researchers have reported GPC, yield, fertilizer P, and STP data, the available data suggests positive correlations between GPC and grain yield, STP, and fertilizer P application. Schlegel and Havlin (1995) reported that addition of P fertilizer increased corn GPC in a 30-year study in Kansas. Mallarino (1996) reported a positive linear relationship between corn GPC and STP in a study encompassing 25 sites over two years in Iowa. Mallarino also reported a significant, positive effect of P fertilization on corn GPC, and found a significant quadratic-plateau relationship when using corn GPC to predict relative yield of corn. Prater (2007) found positive responses of corn and soybean GPC to P fertilization in a 12-year study of corn and soybeans in Iowa, but reported that these responses were less consistent for corn. Prater also reported a positive curvilinear relationship between STP and GPC for both corn and soybeans, and a positive linear relationship between total grain P removal and GPC for both corn and soybeans. Prater, however, did not find a significant relationship between GPC and yield for either corn or soybeans and suggested the use of average GPC values for calculation of net P removal. Heckman et al. (2003) found that both corn yield and Mehlich 3-P STP were significant predictors of corn GPC in a multiple regression model, and suggested future research to refine estimates of the sources of variation in corn nutrient concentrations. While no researcher recommended the use of yield, fertilizer P, and STP data to predict GPC, the overall trends apparent in these studies suggest the possibility.

As farmers increase their use of geo-referenced data collection, there is increasing availability of spatial information on grain yield, STP values, and fertilizer P rates. If these variables can be used to improve GPC estimates, then there is high potential to improve estimates of P removal and to improve fertilizer P recommendations for corn and soybean production. Our objective was to review literature and examine relationships between corn and soybean GPC and grain yield, STP, and fertilizer P rate with the goal of answering two questions. First, do consistent relationships exist between corn and soybean GPC and grain yield, STP, and fertilizer P rate? Second, can we improve the accuracy of corn and soybean GPC predictions by including grain yield, STP, and fertilizer P rates in a GPC model?

Materials and Methods

We compiled a dataset of STP, grain yield, fertilizer P application, and GPC by conducting a thorough review of the primary literature. We searched online databases using Google Scholar and ISI Web of Science. The citation indices of initial papers were used to identify additional relevant publications. When deemed appropriate, we also contacted soil fertility researchers from the North-Central region. The final dataset for corn included 268 observations from six sources, and our final dataset for soybeans included 172 observations from four sources (Table 1-1).

Data from all sources were converted to common units for yield (kg ha^{-1} at 15.5% moisture for corn, kg ha^{-1} at 13% moisture for soybeans), P fertilizer rate (kg P ha^{-1}), and GPC (g P kg^{-1} grain, 0% moisture basis). The STP data was reported as Bray P1. Within data sets, Bray P1 soil tests that were associated with soil samples having pH values >7.4, which is above the recommended soil pH range for the Bray P1 test (Frank et al., 1998; Rehm and Schmitt, 1993), were removed from our analysis. While the mean soil pH for the Schlegel and Havlin (1995) dataset was 8.0 (24 datapoints), there was no evidence of substantial pH variability within this study, and since the reported GPC values were consistent with other datasets, we retained this dataset in our analysis. We removed one data point from the Prater soybean dataset which had a GPC value >3 standard deviations above the mean. When not reported, crop P removals were calculated on a kg P ha^{-1} basis by adjusting GPC for crop moisture and multiplying by grain yield.

Barber (1979) reported average grain yields, average GPC, and annual fertilizer P applications. However, only beginning and ending STP values were reported. We calculated multi-year average STP values for each P treatment by assuming a linear change in STP between the initial and final soil test. Mallarino (1996) reported GPC and fertilizer P rates for each of four P treatments, but reported only two yields – one yield for the 0 P treatment, and one average yield for the 25, 50, and 75 kg P ha^{-1} treatments, because there was no significant difference in yield across these three P rates. We used the average yield reported for P treatments for each of these three P rates. Data presented by Randall (2010) was augmented with additional detail on the same experiments presented in Randall and Vetch (2009). All other research data are presented directly as reported.

We conducted exploratory data analysis by plotting crop P removals against grain yield and GPC and by plotting corn and soybean GPC individually against STP, grain yield, and fertilizer P rate. In all cases, significance is reported at α=0.05. P removal was regressed against grain yield and GPC and corn and soybean GPC were regressed against yield, P fertilizer rate, STP, and all potential interaction effects using the *step* and *lm* procedures in R version 2.12.1 (R Development Core Team, 2010). We determined a best linear fit model using backwards stepwise elimination, with our criterion being minimization of the Akaike information criterion (AIC) value.

Results and Discussion

Grain P removals, yield, and GPC

Relationships between grain P removal, grain yield, and GPC are shown in Fig. 1-1. Differences in yield explained the greatest proportion of total variation in grain P removal for both corn and soybean. However, the wide variation in GPC also contributed to wide differences in grain P removals. This suggests potential for substantial improvement in grain P removal estimates through better understanding of the factors influencing GPC.

Corn

The mean of all 268 corn GPC data points (2.69 g kg^{-1}) was below the range of corn GPC values published by North-Central extension services (3.2 - 3.5 g kg^{-1}) (Rehm, 2001; Sawyer et al., 2008; Vitosh et al., 1995), and the mean GPC value fit the data most poorly, as it had the highest AIC and SSE values (Table 1-2). All experimental data showed a consistent pattern in the response of corn GPC to STP (Fig. 1-2). This pattern was characterized by an initially steep increase in GPC values with STP increases up to approximately 20 mg kg^{-1}, followed by a more gradual GPC response at higher STP values. While the patterns of response within individual trials were similar, the absolute values of the GPC response varied considerably. A linear regression of GPC against STP showed a significant positive response with a coefficient of determination (R^2) of 0.30. A linear regression of GPC against natural-log transformed STP fit the data better (R^2=0.37). We observed a similar pattern in the response of corn GPC to fertilizer P rate (Fig. 1-3). This pattern was most easily discerned in the data from Barber, but similar responses were present in each dataset. Regression of GPC against fertilizer P rate exhibited a significant positive response (R^2=0.13). The relationship between corn GPC and corn yield (Fig. 1-4) was less consistent. Four experiments (Schlegel and Havlin, Mallarino, Randall, Randall and Vetch) exhibited a positive relationship between corn GPC and corn yield across all yield levels. Data from Barber showed a positive relationship between GPC and yield at lower yield levels, followed by a nearly vertical slope in the response curve, suggesting excess uptake of P in corn grain. Data from Prater did not exhibit a statistically significant relationship between yield and GPC. Overall, regression of GPC against grain yield showed a significant positive relationship. However, grain yield explained a small amount of the variation in GPC, as this regression had a R^2 of only 0.03.

Upon regression of corn GPC against grain yield, STP, fertilizer P rate, and interaction terms, we determined that the best-fitting model for predicting corn GPC was a model that included fertilizer P rate and natural-log transformed STP. Values for R^2, AIC, and the sum of squared errors (SSE) for each model are given in Table 1-2. Diagnostic tests of the model indicated constant error variance and normal distribution of error terms at a significance level $\alpha = 0.05$. The full model explained approximately 2% more of the variability in the data than any single factor alone (Table 1-2). Predicted GPC values for a range of yield, STP, and P rate values are shown in Table 1-3. As STP increased, higher concentrations of P were found in the grain. Fertilizer P additions resulted in higher GPC across all yield levels. Within many individual datasets, model fitting indicated that higher yield levels were associated with higher GPC values, even after accounting for the effects on yield of higher STP values and higher fertilizer P rates. However, inclusion of corn yield as a model parameter did not result in a better fit across all datasets. Inclusion of interactions terms did not improve the model fit when datasets were analyzed individually. While inclusion of interaction terms slightly improved the fit of the model across all datasets, trends in the resulting predictions were not always consistent with observed trends within any individual dataset. For this reason, we did not include interaction terms in our final model for corn GPC.

Limits of this model must be noted. The average value of the 95% confidence interval for the model was +/- 0.1 g kg^{-1}, and the average value of the 95% prediction interval for the model was +/- 0.7 g kg^{-1}. Differences between observed and predicted GPC values for all data points are shown in Fig. 1-5. There were no apparent trends in errors across the range of observations. For making new predictions of GPC, we advise limiting yield, STP, and P rate inputs to values within the ranges suggested in Fig. 1-5. While observed model errors outside this range were relatively small, errors of new predictions may be large.

The R^2 of 0.39 for the full model indicates that STP and fertilizer P explain less than half of the total variation in corn GPC. These results are comparable with those of Heckman et al. (2003), who reported a R^2 of 0.4 for a linear GPC model of GPC regressed against grain yield and Mehlich 3P STP. The higher GPC values reported by Heckman et al. (2003) may be attributed to the extremely high STP values (range 36-418 mg kg^{-1}, mean 133 mg kg^{-1}) of the soils included in that experiment. Additional variables clearly influence GPC and could account for the unexplained variation in our model. Previous publications have reported that water availability, corn hybrid, soil variability, and weather have significant effects on GPC (Eghball et al., 2003; Heckman et al., 2003). Data from this study spanned nearly six decades of climate variability and genetic increases in yield potential. We were not able to observe effects on GPC directly attributable to climate variability or to genetic development. Soil pH has well-established effects on soil P availability (Brady and Weil, 2002), and could influence GPC. All known soil pH values in this study were between 5.1 and 8.0, and <10% of data sources were outside of the range from 5.5 to 7.0, in which P availability is highest (Brady and Weil, 2002). Within the dataset, we did not observe a significant relationship between soil pH and GPC. Plant availability of P differs between some P forms (Ebeling et al., 2003; Shahandeh et al., 2008) and GPC could be influenced by P source, but plant availability of P is equivalent among the fertilizer P sources in this dataset (Rehm et al., 2002), and we observed GPC to behave similarly across P sources. GPC data from Barber (1979) and Randall (2010) includes multiple fertilizer P placement methods, but both Randall (2010) and Prater (2007) reported no significant effect of P placement on GPC.

While our model explicitly excludes consideration of these other variables, our equation does describe expected mean GPC values that result from significant relationships with STP and fertilizer P. Moreover, the broad agreement among the datasets included in this study indicates that these trends have been consistent throughout the North-Central United States over the multi-decadal time-scales.

When comparing the results of our model to recommended average GPC values, we found that 99% of the fitted GPC values of our model fell below the lower bound of the range of recommended GPC estimates. In 97% of cases, the upper 95% confidence interval of our model fell below the range of recommended GPC estimates. In 25% of cases, the upper 95% prediction interval of our model fell below the lower bound of the range of recommended GPC estimates. The fitted corn GPC value of our model fell above the range of recommended GPC estimates in no cases, and the lower 95% confidence and prediction intervals never exceeded the upper bound of the range of GPC estimates. We conclude that current recommended values for corn GPC considerably over-estimate actual GPC values across a broad range agronomic conditions, with the greatest over-estimation when STP < 20 mg kg^{-1} Bray P1, corn yield < 10,000 kg ha^{-1}, and no fertilizer P is applied . Under typical production conditions in the United States (10,350 kg ha^{-1} yield, 25 mg kg^{-1} Bray P1 STP, and 0 kg P ha^{-1} applied, or 10,350 kg ha^{-1} yield, 15 mg kg^{-1} Bray P1 STP, and 25 kg P ha^{-1}) (Fixen et al., 2010; NASS, 2011; Sawyer et al., 2008), our model indicates that current guidelines over-estimate total corn grain P removals by 25-35%. Even at the upper end of the current range of yield and

STP, current guidelines over-estimate total P removals by 25%. However, given trendline corn yield increases and expectations for considerably higher corn yields in the near future (Elmore, 2009; Randall, 2010), the trends indicated by this analysis suggest that future corn crops will remove substantially more P per hectare than today's crops. If current fertilizer P recommendations have been accurately calibrated for maintaining STP values under historical yield levels, we expect future higher corn yield levels to require substantially higher maintenance P applications. Higher maintenance P applications may, in turn, lead to higher GPC values and larger P removals.

Soybeans

The mean of all 172 soybean GPC data points (6.12 g kg^{-1}) was below the range of soybean GPC values published by North-Central U.S. university extension services (6.7 - 7.5 g kg^{-1}) (Rehm, 2001; Sawyer et al., 2008; Vitosh et al., 1995), and the mean GPC value fit the data poorly, as it had the highest AIC and SSE values (Table 1-3). All soybean experiments reflected a consistent pattern in the response of soybean GPC to STP (Fig. 1-6). Soybean GPC increased rapidly with increasing STP up to approximately 20 mg kg^{-1} Bray P1, with a more gradual increase in GPC through the upper limit of the observed STP range. A linear regression of GPC against STP showed a significant positive response and had a R^2 of 0.49. A linear regression of GPC against natural-log transformed STP fit the data better (R^2 = 0.60). There was considerably less scatter in the soybean data than in the corn data, which is reflected in the higher R^2 value. Soybean GPC also responded positively to fertilizer P rate (Fig. 1-7). Although the pattern is again most easily discerned in Barber's data, the positive response of GPC to fertilizer P rate is also present in the data of Prater and of Randall and Vetch. Randall (2010) did not apply P to the soybean crop. Linear regression of GPC against fertilizer P showed a significant positive response with a R^2 of 0.28. A significant positive relationship was also found between soybean GPC and soybean yield in all four experiments (Fig. 1-8), with a R^2 of 0.31.

We determined the best-fitting model for soybean GPC to include yield, fertilizer P rate, and natural-log transformed STP. Values R^2, AIC, and SSE for each model are given in Table 1-4. Diagnostic tests of the best-fitting model indicated constant error variance and normal distribution of error terms at a significance level $\alpha = 0.05$. The full model explained approximately 3% more of the variability in the data than any single factor. Predicted GPC values for a range of yield, STP, and P rate values are shown in Table 1-3. The terms of this model agree with basic agronomic principles. As STP and fertilizer P increased, the P concentration in the soybean seed increased. GPC increased with higher yield levels, even after accounting for the effects on yield of higher STP values and higher fertilizer P rates. The fit of this model (R^2=0.63) indicates that these variables explain a considerable proportion of the total variation in soybean GPC. Potential effects of cultivar, climate, soil pH, fertilizer P source, and P placement were described in the discussion of corn GPC, and apply here as well. While our model explicitly excludes consideration of other variables, our equation does describe expected mean GPC that result from significant relationships among STP, fertilizer P, and yield. Similar responses across datasets indicate that these trends are consistent throughout the North-Central United States over multi-decadal time-scales.

The average value of the 95% confidence interval across the range of observed yield, STP, and P rate was +/- 0.2 g kg^{-1}, and the average value of the 95% prediction interval was 1.2 g kg^{-1}. As with corn, the limits of this soybean GPC model must be noted. It is suitable for estimating mean GPC for a given set of value for yield, STP, and fertilizer P rate. There is a 95% confidence level that the relative error for single new predictions is <+/-20%. Differences between observed and predicted GPC values for all data points are shown in Fig. 1-5. There were no apparent trends in errors across the range of observations. For making new predictions of GPC, we advise limiting yield, STP, and P rate inputs to values within the ranges suggested in Fig. 1-5.

When comparing the results of our model to the recommended soybean GPC values, we found that 62% of the fitted GPC values of our model fell below the lower bound of the range of recommended GPC estimates. In 56% of cases, the upper 95%

confidence interval of our model fell below the lower bound of the range of recommended GPC estimates. In 23% of cases, the upper 95% prediction interval of our model fell below the lower bound of the range of recommended GPC estimates. The fitted soybean GPC value of our model never fell above the upper bound of the range of recommended GPC estimates, nor did the lower 95% confidence and prediction intervals ever exceed the upper bound of the range of GPC estimates. We conclude that current recommended values for soybean GPC over-estimate actual GPC values in many agronomic conditions, with greatest over-estimation under conditions of low STP and low soybean yield. Under typical production conditions in the United States (3000 kg ha^{-1} yield, 25 mg kg^{-1} Bray P1 STP, and 0 kg fertilizer P ha^{-1}) (Fixen et al., 2010; NASS, 2011; Sawyer et al., 2008), current guidelines are higher than the removals indicated by our soybean GPC model by 10-20%.

Conclusions

Variation in GPC is an important component of variation in crop P removal. Current university extension service guidelines for the North-Central United States are based on constant values of GPC concentration. This research indicates that these recommended GPC estimates for corn and soybeans are often too high. Our model of GPC indicates that actual P removal is lower than current North-Central U.S. extension service guidelines for corn and soybeans across all STP values, common P fertilizer rates, and yield levels, but is substantially lower than current guidelines at yields below the U.S. trendline yields of ~10,000 kg ha^{-1} for corn and ~3,000 kg ha^{-1} for soybeans (Elmore, 2009; NASS, 2011) and at STP values below the U.S. Corn Belt mean of 25 mg kg^{-1} (Fixen et al., 2010). Given that approximately 50% of soil tests from the North-Central region fall below critical STP values (Fixen et al., 2010) and available data suggests that the distribution of corn and soybean yields across the landscape is negatively skewed (Bakhsh et al., 2000; also Fig. 1-9), we expect that current guidelines over-estimate current crop P removals on a substantial portion of production acres.

Inclusion of STP, yield, and fertilizer P rate as predictors of GPC may improve the accuracy of GPC estimates. Increasing availability of STP, yield, and fertilizer P maps suggests the use of this data to refine spatial estimates of P mass-balance.

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Table 1-1. Sources and attributes of experimental data used for analysis of relationship between grain phosphorus concentration, grain yield, fertilizer phosphorus (P) application, and soil test P.

Crop	Author	Number and location of sites	Years of experiment	P Rates ($kg\ ha^{-1}$)	P Source	Placement	Soil pH	Data presented as:
Corn	Barber, 1979	1 (Indiana)	1952-1977	0,5,11,22,44,49,54	SP†	Broadcast, band	6.5	Multi-year average
	Schlegel and Havlin, 1995	1 (Kansas)	1988-1991	0,19.375	TSP‡	Broadcast	7.9-8.1	Annual
	Mallarino, 1996	21 (Iowa)	1989-1990	0,25,50,75	TSP‡	Broadcast	5.1-7.0	Annual by site
	Prater, 2007	5 (Iowa)	1994-2005	0,28	TSP‡	Broadcast	Not given	Annual by site
	Randall, 2010; Randall and Vetch, 2009	2 (Minnesota)	2005-2007	0,10,20; 0,12.5,25	DAP,§ 10-15-0	In-furrow, deep-band, broadcast	5.9	Multi-year average
	Randall and Vetch, 2010	1 (Minnesota)	2008	0			5.9	Annual by placement
Soybean	Barber, 1979	1 (Indiana)	1952-1977	0,5,11,22,44,49,54	SP†		6.5	Multi-year average
	Prater, 2007	5 (Iowa)	1994-2005	0,28	TSP‡	Broadcast	Not given	Annual by site
	Randall, 2010; Randall and Vetch, 2009	2 (Minnesota)	2006-2008	0			5.9	Multi-year average
	Randall and Vetch, 2010	1 (Minnesota)	2009	0,49	TSP‡	Broadcast	5.9	Annual by placement

† Superphosphate
‡ Triple superphosphate
§ Diammonium phosphate

Table 1-2. Parameters and statistics for corn grain phosphorus concentration (GPC) models .

Model	R^2	AIC	SSE	Variable	Coefficient
GPC ~ fertilizer P	0.13	331.00	52.76	Intercept	2.523
				P rate	$7.682 * 10^{-3}$
GPC ~ Yield	0.03	360.92	58.99	Intercept	2.302
				Yield	$4.112 * 10^{-5}$
GPC ~ Soil Test P	0.30	272.12	42.36	Intercept	2.269
				STP	$1.950 * 10^{-2}$
GPC ~ ln (Soil Test P)	0.37	245.37	38.33	Intercept	1.539
				ln (STP)	$4.050 * 10^{-1}$
Full Model	0.39	239.67	37.25	Intercept	1.582
				ln (STP)	$3.665 * 10^{-1}$
				P rate	$3.082 * 10^{-2}$
GPC ~ Mean GPC (reflects goodness-of-fit for using constant GPC value)	0	366.83	60.76	Intercept	2.685

Table 1-3. Grain phosphorus concentration (GPC) model predictions for a range of crop yields, soil test phosphorus (STP) values, and fertilizer phosphorus rates (P rate) for corn and soybeans. English units are included for comparison to published North-Central U.S. university extension service recommendations.

Corn					Soybean				
Yield	STP	P rate	GPC	GPC (15.5% moisture)	Yield	STP	P rate	GPC	GPC (13% moisture)
(kg ha^{-1})	(mg kg^{-1})	(kg ha^{-1})	(g kg^{-1})	(lb P_2O_5 bu^{-1})	(kg ha^{-1})	(mg kg^{-1})	(kg ha^{-1})	(g kg^{-1})	(lb P_2O_5 bu^{-1})
8,000	10	0	2.43	0.26	2500	10	0	5.48	0.59
8,000	25	0	2.76	0.30	2500	25	0	6.17	0.67
8,000	40	0	2.93	0.32	2500	40	0	6.52	0.71
8,000	10	50	2.58	0.28	2500	10	25	5.65	0.61
8,000	25	50	2.92	0.32	2500	25	25	6.34	0.69
8,000	40	50	3.09	0.33	2500	40	25	6.69	0.72
10,000	10	0	2.43	0.26	3250	10	0	5.71	0.62
10,000	25	0	2.76	0.30	3250	25	0	6.40	0.69
10,000	40	0	2.93	0.32	3250	40	0	6.75	0.73
10,000	10	50	2.58	0.28	3250	10	25	5.87	0.64
10,000	25	50	2.92	0.32	3250	25	25	6.56	0.71
10,000	40	50	3.09	0.33	3250	40	25	6.92	0.75
12,000	10	0	2.43	0.26	4000	10	0	5.94	0.64
12,000	25	0	2.76	0.30	4000	25	0	6.63	0.72
12,000	40	0	2.93	0.32	4000	40	0	6.98	0.76
12,000	10	50	2.58	0.28	4000	10	25	6.10	0.66
12,000	25	50	2.92	0.32	4000	25	25	6.79	0.74
12,000	40	50	3.09	0.33	4000	40	25	7.15	0.77

Table 1-4. Parameters and statistics for soybean grain phosphorus concentration (GPC) models.

Model	R^2	AIC	SSE	Variable	Coefficient
GPC ~ fertilizer P	0.28	447.08	130.84	Intercept	5.682
				P rate	$3.332 * 10^{-2}$
GPC ~ Yield	0.31	438.53	124.5	Intercept	3.348
				Yield	$8.702 * 10^{-4}$
GPC ~ STP	0.49	386.81	92.17	Intercept	5.068
				STP	$5.017 * 10^{-2}$
GPC ~ ln (STP)	0.60	344.43	72.04	Intercept	3.441
				ln (STP)	0.971
Full Model	0.63	335.16	66.69	Intercept	2.986
				Yield	$3.047 * 10^{-4}$
				ln (STP)	$7.524 * 10^{-1}$
				P rate	$6.663 * 10^{-3}$
GPC ~ mean GPC (reflects goodness-of-fit for using constant GPC value)	0	501.28	181.42	Intercept	6.12

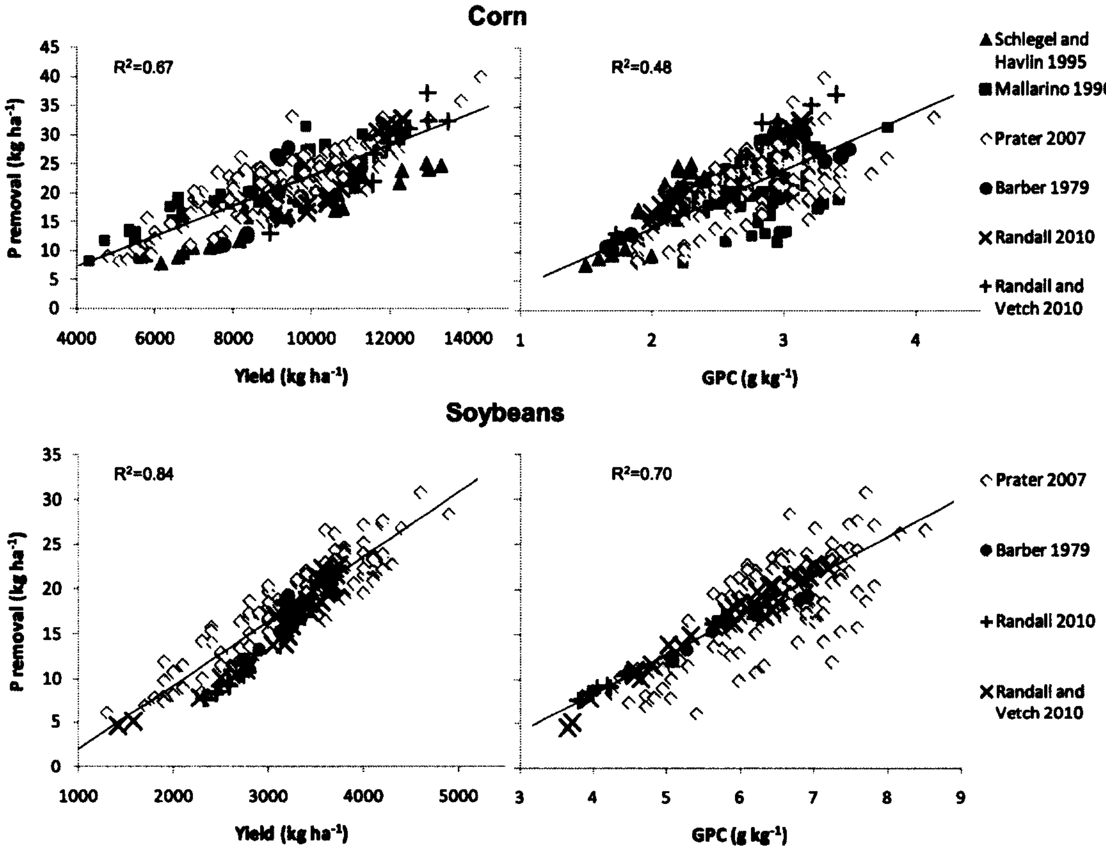

Fig. 1-1. Relationships between grain phosphorus (P) removals (vertical axis) and grain yield (left set of graphs) and grain phosphorus concentration (GPC, right set of graphs) for corn and soybeans by data source. While variation in yield accounts for the largest proportion of the variation in P removal, differences in GPC also account for substantial differences in P removal.

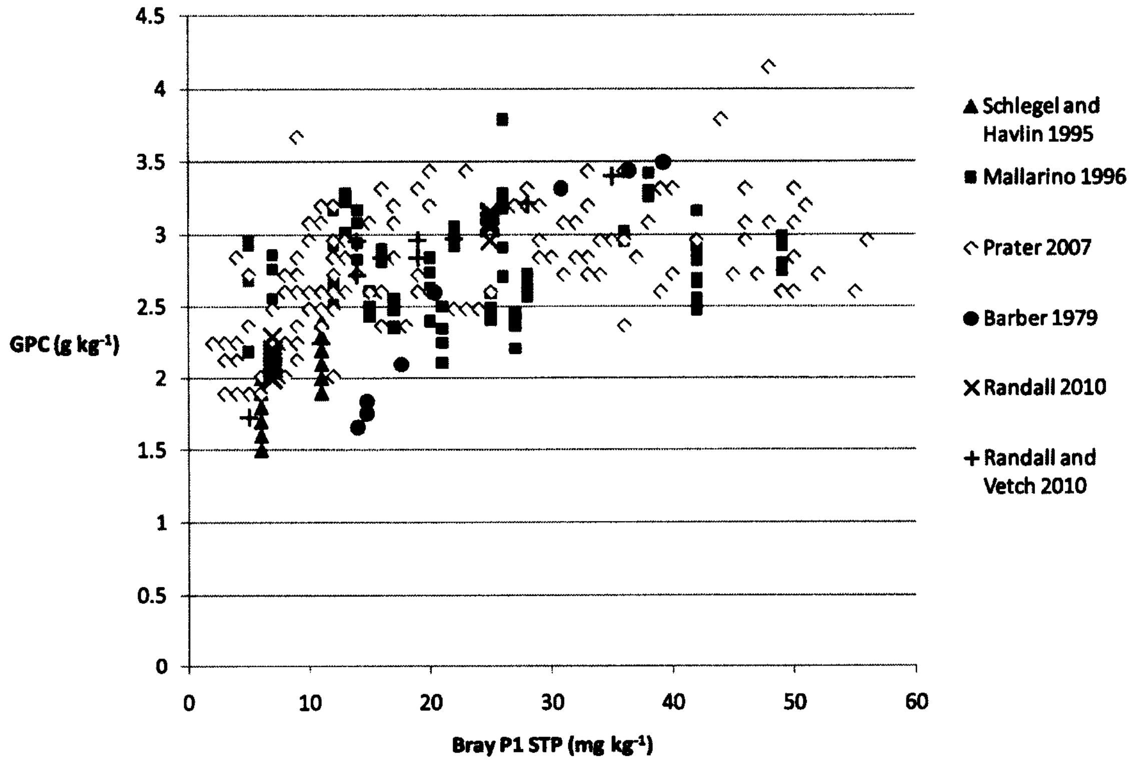

Fig. 1-2. Relationship between experimental corn grain phosphorus concentrations (GPC) and Bray P1 soil test phosphorus (STP) by data source. Shaded gray region indicates range of North-Central U.S. university extension service guidelines for corn GPC. Corn GPC is positively related to STP.

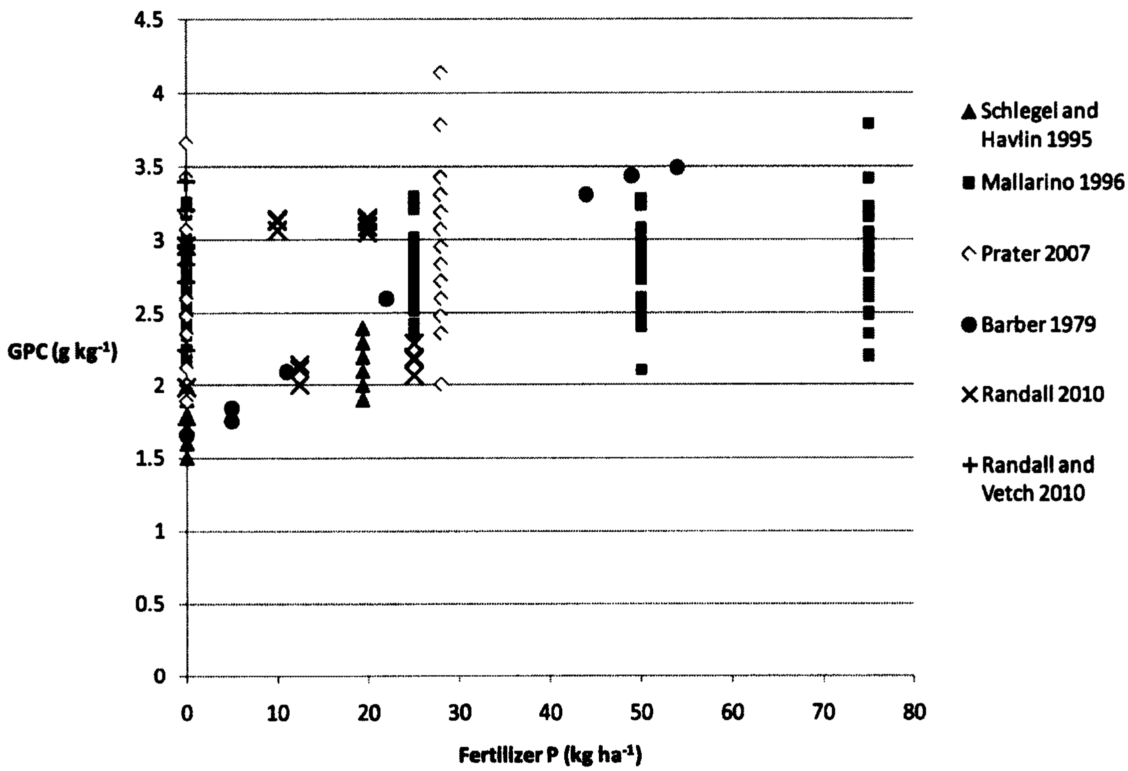

Fig. 1-3. Relationship between experimental corn grain phosphorus concentrations (GPC) and fertilizer phosphorus (P) applied by data source. Shaded gray region indicates range of North-Central U.S. university extension service guidelines for corn GPC. Corn GPC is positively related to fertilizer P rate.

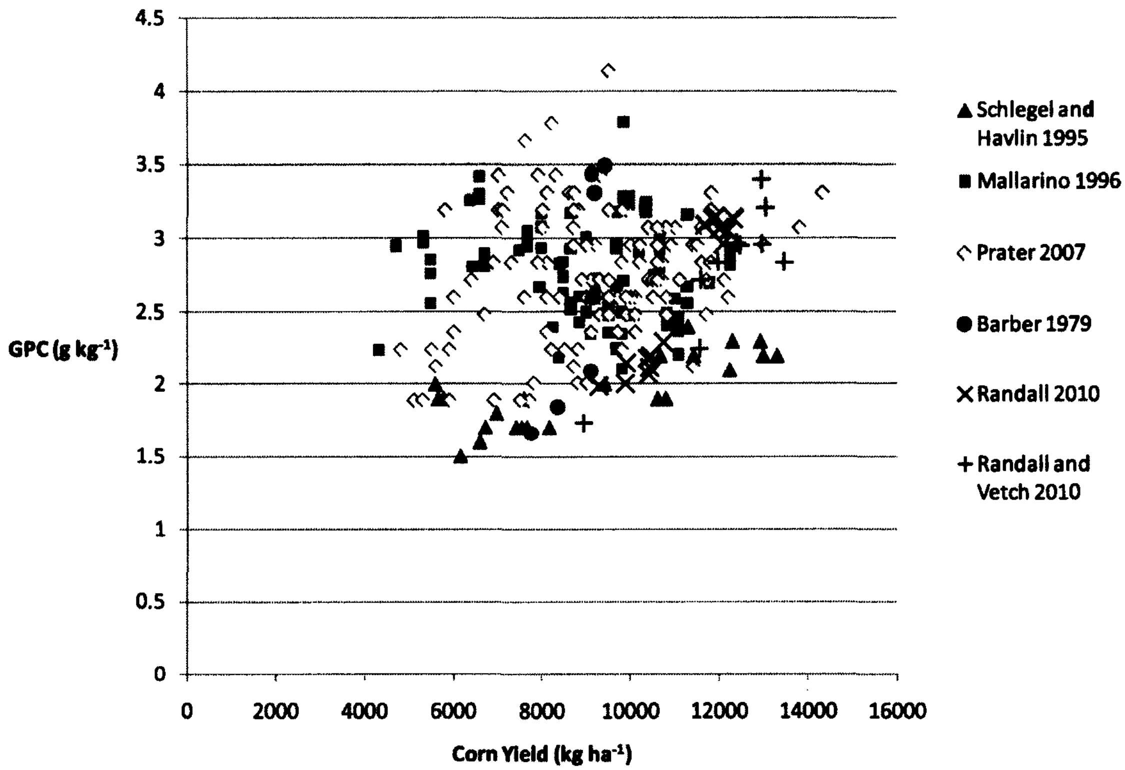

Fig. 1-4. Relationship between experimental corn grain phosphorus concentrations (GPC) and corn grain yield by data source. Shaded gray region indicates range of North-Central U.S. university extension service guidelines for corn GPC. Corn GPC exhibits a weak but positive relationship to corn yield.

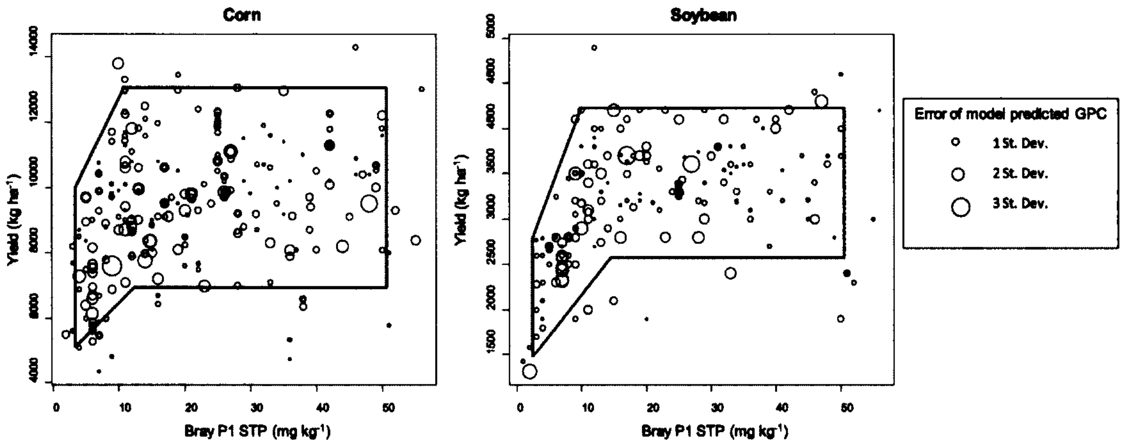

Fig. 1-5. Scatterplots of yield and soil test phosphorus (STP) values for corn and soybean experimental data used to generate grain phosphorus concentration (GPC) model. Scale of marks indicates the error of the model prediction, in standard deviations of error. Black polygons on each scatterplot indicate our recommended limits of yield and STP values upon which new prediction may be made using our model. Fertilizer P rates of 0-75 kg ha^{-1} may be used in the model within these yield and STP limits.

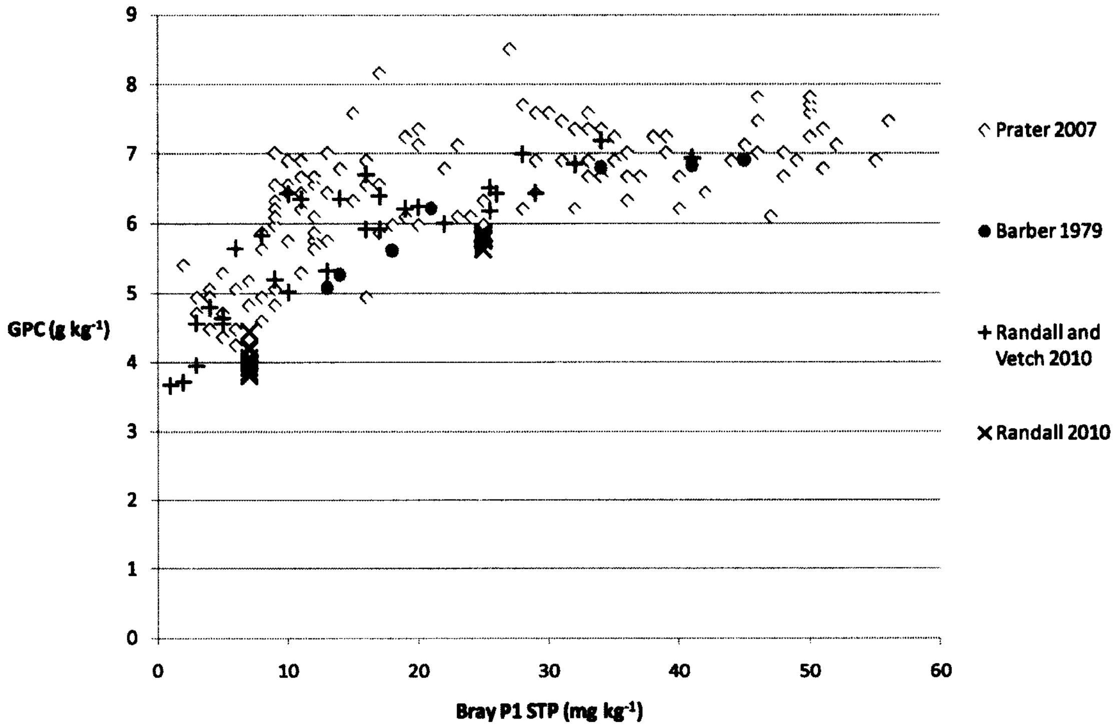

Fig. 1-6. Relationship between experimental soybean grain phosphorus concentrations (GPC) and Bray P1 soil test phosphorus (STP) by data source. Shaded gray region indicates range of North-Central U.S. university extension service guidelines for soybean GPC. Soybean GPC is positively related to STP.

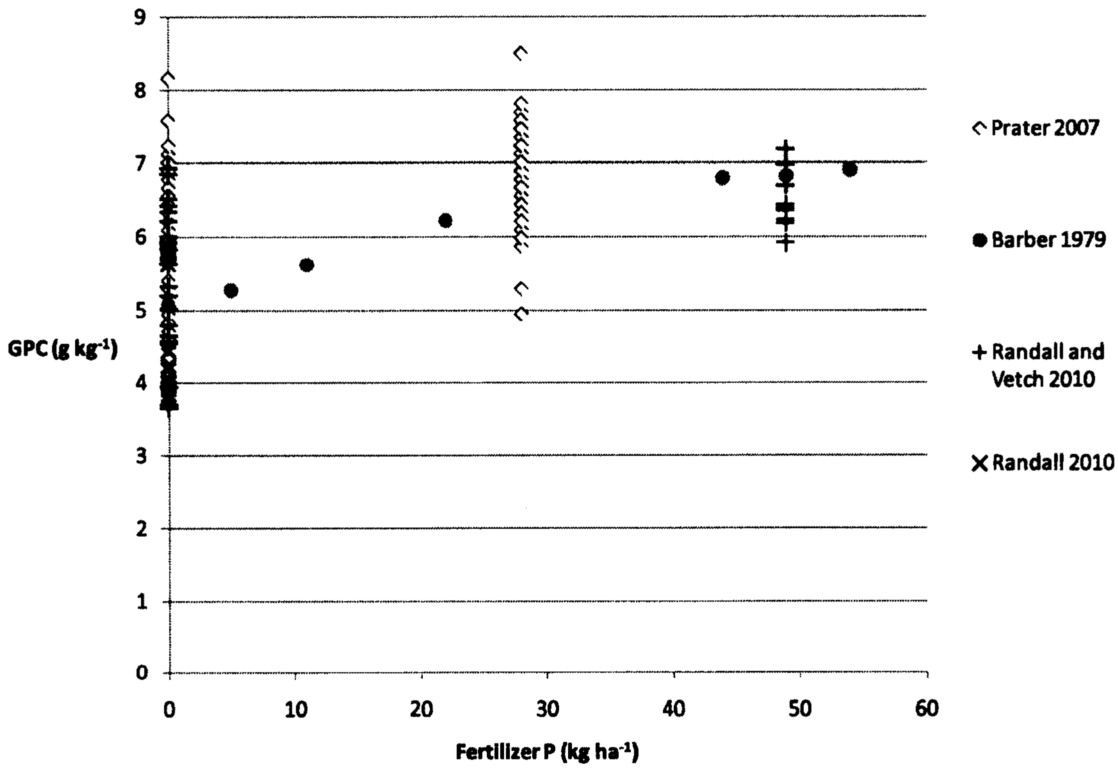

Fig. 1-7. Relationship between experimental soybean grain phosphorus concentrations (GPC) and fertilizer phosphorus (P) applied by data source. Shaded gray region indicates range of North-Central U.S. university extension service guidelines for soybean GPC. Soybean GPC is positively related to fertilizer P rate.

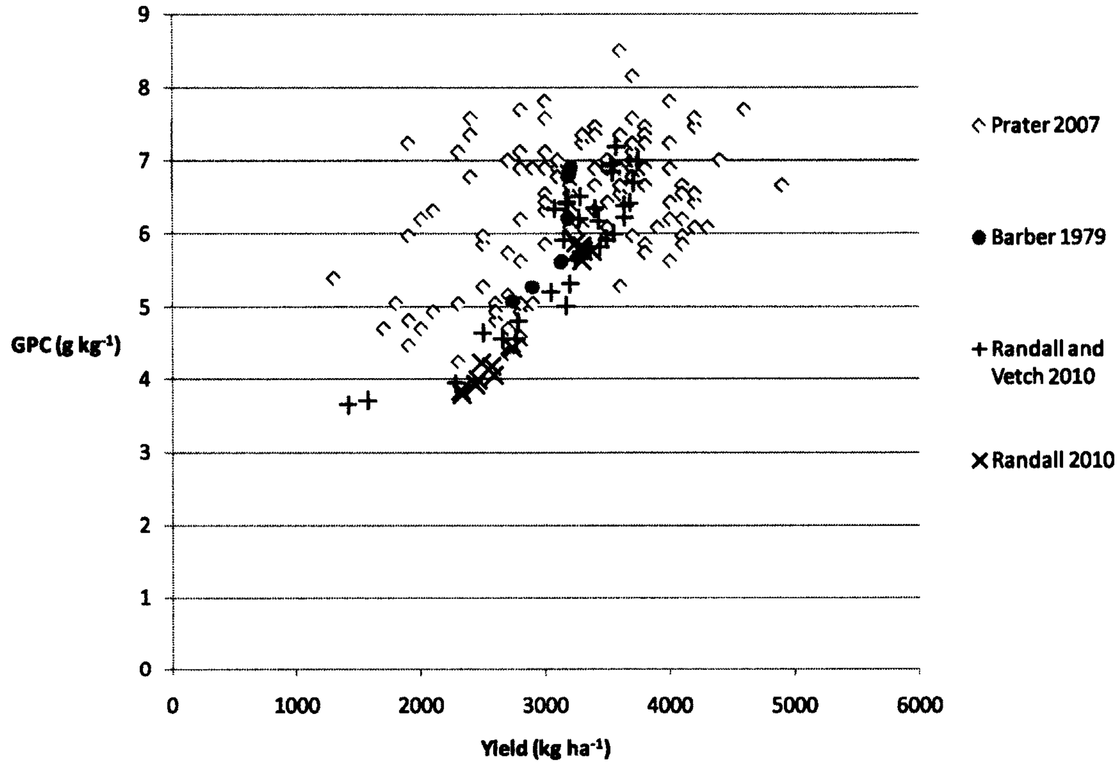

Fig. 1-8. Relationship between experimental soybean grain phosphorus concentrations (GPC) and soybean seed yield by data source. Shaded gray region indicates range of North-Central U.S. university extension service guidelines for soybean GPC. Soybean GPC is positively related to yield.

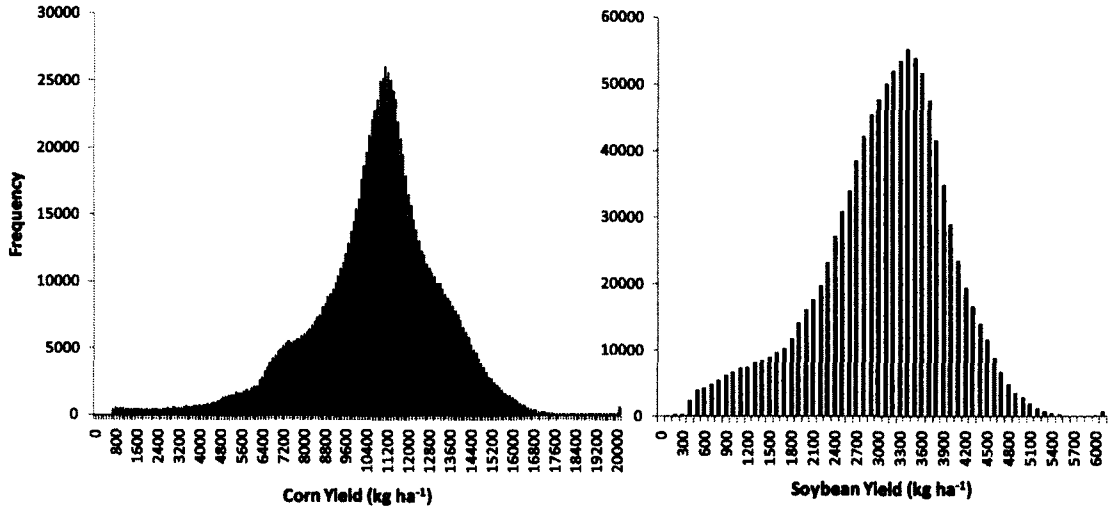

Fig. 1-9. Frequency distribution of yield monitor-recorded corn and soybean yields over 13-year period 1997-2009 on a 1200 ha farm in North-Central United States. Distribution of both corn and soybean yields is negatively skewed.

CHAPTER 2: Soil Nitrogen and Phosphorus Behavior in a Long-Term Fertilization Experiment[1]

ABSTRACT

Accurate fertilizer recommendations rely on quantitative estimation of nutrients supplied by soil and fertilizer nutrients immobilized by soil. Understanding variation in these processes over space and time is critical for site-specific nutrient management. Our objective was to characterize spatial variability in N and P cycling for a corn [*Zea mays* L.]–soybean [*Glycine max* (L.) Merr.] rotation in southern Minnesota glacial-till soils. Soil samples and grain yield measurements were taken annually from 0.014-ha cells within two 16-ha fields. We determined effects of fertilizer P additions and crop P removal on soil test phosphorus (STP) and determined relationships between STP changes and soil variables. We also determined temporal stability of soil mineralizable N and inorganic N. The spatial patterns of mineralizable N were consistent over time. The spatial pattern of soil NO_3–N was consistent with mineralizable N at a well-drained site, but not at a poorly-drained site. Change in STP per kg P net addition or removal exhibited spatial autocorrelation. Declines in STP under net P removal were directly related to initial STP values. Increases in STP under net P addition were significantly related to pH at both sites and mineralizable N at one site. Temporal stability in mineralizable N suggests that predictive approaches to site-specific N management may succeed when the environment for mineralization is uniform. Within-field variability in the relationship between STP and net P addition may substantially affect fertilizer P rates required to attain critical STP values and should be accounted for in variable-rate P applications.

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[1] P. Anthony, G. Malzer, M. Zhang, and S. Sparrow. From Agronomy Journal 104:1223–1237 (2012), with permission, copyright American Society of Agronomy.

Abbreviations: AIC, Akaike information criterion; DAP, diammonium phosphate; DEM, digital elevation model; OM, organic matter; PBMN, phosphate-borate mineralizable nitrogen; STK, soil test potassium; STP, soil test phosphorus; TOC, total organic carbon; +ΔP/ΔSTP, net kg phosphorus addition per 1 mg kg^{-1} increase in STP; -ΔP/ΔSTP, net kg phosphorus removal per 1 mg kg^{-1} decrease in soil test phosphorus.

INTRODUCTION

Variable-rate application of crop fertilizers has become one of the most widely-used site-specific management practices for agricultural fields. By accurately matching fertilizer application rates to crop requirements, this practice has the potential to enhance economic returns to farmers by optimizing use of resources at each point on the landscape (Lambert et al., 2006: Wolf and Nowak, 1995). In addition, environmental impacts associated with excessive fertilization or poor crop growth may be minimized. Adoption of variable-rate fertilizer application has been driven by numerous reports in recent years indicating that a great deal of variability exists in the levels of soil nutrients, and that this variability is spatially correlated at distances of tens to hundreds of meters (Cahn et al., 1994; Cambardella et al., 1994: Robertson et al., 1997). Variability over scales of meters to hundreds of meters is amenable to management by current precision agriculture equipment (Pierce and Nowak, 1999).

For relatively immobile nutrients such as P, current strategies for planning variable-rate applications consist of soil sampling that is both extensive and intensive, using soil test results to map nutrient availability across the field to create a fertilizer application map designed to attain a particular critical soil test value considered optimum for crop production. Many researchers have worked to develop efficient soil sampling designs that allow accurate mapping of soil nutrient levels (Franzen and Peck, 1995; Kravchenko, 2003; Mallarino and Wittry, 2004; Mueller et al., 2004; Wollenhaupt et al., 1994). However, current fertilizer rate recommendations for given soil test levels are designed to be broadly applicable on a regional or state-wide basis (Mallarino, 2009;

Rehm et al., 2006; Sawyer et al., 2008). There are sound reasons to expect that the quantity of nutrient addition required for a unit change in soil test level may differ among soils. These reasons include differences in sorption capacity, mineralization, and fixation capacity, and nutrient loss or accumulation due to runoff and erosion. While a number of researchers have reported soil test incline or decline rates on uniform plots in response to fertilization (Barber, 1979; Dodd and Mallarino, 2005; Leikam, 1992; Randall et al., 1997; Webb et al., 1992), we are not aware of studies that report on differences in soil test incline or decline rates within fields. Lack of such information hinders the optimization of site-specific management for two reasons. First, both accuracy and precision of fertilizer P rate recommendations are reduced, potentially leading to higher variability in soil P (Wittry and Mallarino, 2004) and associated environmental consequences (Mallarino et al., 2001), and also reducing the ability of the producer to rapidly attain the most profitable soil test value (Lowenberg-DeBoer and Reetz, 2002). Second, lack of site-specific information on soil test incline or decline rates prevents site-specific economic optimization of P, as this calculation requires not only knowledge of the relationship between yield and STP, but also knowledge of the quantity and cost of fertilizer P required to effect a unit change in the STP value.

Challenges of site-specific N management are different from those involving P, primarily because of the transient nature of soil N. In contrast to P, fertilizer N that is not used by a crop cannot reliably be banked in the soil from year to year, and both the spatial and temporal variability in soil N provide limitations to the potential accuracy of fertilizer N recommendations (Meisinger et al., 2008). However, mineralization of organic soil N can meet a substantial proportion of the total crop N needs (Davis et al., 2003; Ma et al., 1999). Previous research comparing single-year mineralization tests to long-term crop response has suggested that once N mineralization values have been established for a single site, these data may be useful for predicting mineralization over many years (Bundy, 2006; van Schaik, 1998). Goovaerts and Chiang (1993) showed persistence in the spatial structure of mineralizable N over a period of months; however, we are not aware of literature that demonstrates the temporal stability of N mineralization values over several years.

A large number of studies have looked at spatial variability in soil inorganic N, identifying significant spatial variation (Cahn et al., 1994; Cambardella et al., 1994; Kaspar et al., 2004; Robertson et al., 1997). Fewer studies have looked at spatial patterns of soil N over time, and these have identified both significant temporal variability (Cain et al., 1999) and temporal stability (Dharmakeerthi et al., 2005) within years. Shahandeh et al. (2005) and Kay et al. (2006) compared the spatial pattern of soil N variability among years with samples taken at the same time of the year and reported between-season variability in the spatial patterns of soil N. Despite extensive study of spatial variation in soil N, there is little information available that relates spatial variability of mineralizable N to spatial variability of inorganic N. The degree of temporal stability of spatial patterns in potential N mineralization and the relationship of these patterns to inorganic N availability both have important implications for site-specific N fertilization strategies. If these patterns are stable over time, efforts to predict optimum N fertilizer rates are more likely to succeed; if they are not stable, site-specific N management must rely more heavily on in-season sensing of the crop and soil.

The objectives of our research were to determine soil test values and spatial structure of mineralizable N, inorganic N, and available P at two field sites over 6 yr; to determine STP response to fertilizer additions and crop removals; and to determine relationships between rates of change in STP values and other attributes of the soil and landscape.

MATERIALS AND METHODS

Site Description and Crop Management

Field experiments were established in the fall of 2001 on two 16-ha fields in south-central Minnesota. The two fields are located in Nicollet County (AN site, 44°23′

N, 94°08′ W) and Brown County (WB site, 44°08′ N, 94°41′ W). The sites were initially developed for agriculture in the 1860s, and have been in a corn–soybean rotation since the 1960s. The soils at site AN lie within a Clarion–Canisteo–Webster association, and consist of the of Canisteo series (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), Harps series (fine-loamy, mixed, superactive, mesic Typic Calciaquolls), Le Sueur series (fine-loamy, mixed, superactive, mesic Aquic Argiudolls), Cordova series (fine-loamy, mixed, superactive, mesic Typic Argiaquolls), Okoboji series (fine, smectitic, mesic Cumulic Vertic Endoaquolls), and Lester series (fine-loamy, mixed, superactive, mesic Mollic Hapludalfs) (Jackson, 1994; USDA-NRCS, 2011). The soils at site WB lie within a Nicollet–Clarion–Webster association, and consist of the Canisteo series, Clarion series (fine-loamy, mixed, superactive, mesic Typic Hapludolls), Nicollet series (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Okoboji series, and the Fieldon–Canisteo complex (fine-loamy to coarse-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) (Christensen, 1998; USDA-NRCS, 2011). Soils at both sites formed from calcareous glacial till. Neither site had a history of manure application in the 5 yr before initiation of the research. Site AN is systematically tile drained on 30-m spacings; lateral drains run East–West or North–South depending on topography. Site WB has limited tile drainage.

Experimental Design

The experiment included three replications of nine fertilizer treatments in a randomized complete block, split plot design (Fig. 2-1). Phosphorus (0 and 56 kg P ha^{-1}) was the main plot. Diammonium phosphate (DAP, 18–46–0) was used as the P source due to unavailability of other P products in local markets. Subplots of N treatments (0, 50, 101, 152, and 202 kg N ha^{-1}) were applied in randomized strips within the main plots. Because DAP was the P source, there was no 0 kg N ha^{-1} treatment within those plots where P was applied. The DAP rate was selected to meet or exceed anticipated crop P removal (Sawyer et al., 2008) and provided N at a rate of 50 kg ha^{-1}. One extra 101 kg N

ha^{-1} N strip was included in each whole plot to avoid having 0 kg N ha^{-1} treatments repeated on the same strip in consecutive rotations; instead, the 0 kg N ha^{-1} treatments were applied to a strip that had received a 101 kg N ha^{-1} rate in the previous N application. The 101 kg N ha^{-1} rate was chosen for this purpose because it corresponded to the University of Minnesota recommended N rates for corn in a corn–soybean rotation (Rehm et al., 2006) and was expected to provide adequate N for the crop while minimizing carryover NO_3–N. All other treatments were applied to the same strip in each year of application. Identical designs were applied at both sites. Potassium was applied to the entire field at a rate of 93 kg K ha^{-1}. This rate was chosen to correspond to crop removal based on anticipated yields and the nutrient content of harvested crops. All fertilizers were applied before the corn year of the corn–soybean rotation. Nitrogen was applied as anhydrous ammonia (82–0–0) with the nitrification inhibitor nitrapyrin (Dow AgroSciences, Indianapolis, IN), P was applied as DAP, and K was applied as muriate of potash (KCl, 0–0–60) at both sites in November 2001 and November 2003, and at site WB in November 2005. In April 2006, N was applied as anhydrous ammonia without nitrapyrin, P was applied as DAP, and K was applied as muriate of potash at site AN. An additional P treatment was imposed at site WB in 2006 and 2007, so STP analysis at this site was conducted using only 2001 to 2005 data.

Soil Chemical and Topographical Variables

We sampled soils in the fall of each year during 2001 to 2007. For sampling, each 9-m wide N plot was subdivided into 15-m long segments, creating 9- by 15-m (0.014-ha) grid cells. At site AN, each of the 36 N plots consisted of 22 cells and was 330 m in length, for a total of 792 grid cells; at site WB, each of the 36 N plots consisted of 23 cells and was 345 m in length, for a total of 828 grid cells. In the fall of each year 2001 to 2003 we took soil samples from each grid cell in six plots that alternated between a 101 kg N ha^{-1} treatment and a 0 or 50 kg N ha^{-1} treatment, totaling 132 samples per year at site AW and 138 samples per year at site WB. In the falls 2004 to 2007, we sampled each grid cell in 12 plots, totaling 264 samples per year at site AN and 276 samples per year at site WB. These plots included six of the plots sampled from 2001 to 2003 and six 202 kg N ha^{-1} treatments. In each fall, samples were taken to a 15-cm depth from each selected cell using a 2.5-cm diam. open-end regular soil probe with an adjustable step. Each sample was a composite of six soil cores taken from the center of each grid cell and from points on a circle of 3-m radius centered in each cell. These soil samples were placed in paper bags, dried in a forced-air oven at 32°C within hours of sampling, and ground with a hammer-mill to pass a 2-mm sieve. Samples were extracted using Bray P1, Olsen P, ammonium-acetate K, and DTPA Zn extractions as described in Brown (1998). Phosphorus was determined using colorimetric methods on a Brinkmann PC 800 probe colorimeter (Brinkmann Instruments, Westbury, NY). Potassium was determined using a PerkinElmer AAnalyst 100 AA Spectrophotometer (PerkinElmer Corporation, Waltham, MA) set on emission mode at 776 nm. Zinc was determined using an ARL 3560 inductively-coupled plasma atomic emission spectrophotometer (Applied Research Laboratories, Crawley, Sussex, UK). Soil pH and organic matter (OM) were determined according to Brown (1998). In the fall of 2001 and each succeeding odd-numbered fall, 0- to 60-cm samples were also taken from each selected cell following soybean harvest. Each sample consisted of one 5-cm diam. core taken with a truck-mounted Giddings hydraulic probe with a quick-relief tip (Giddings Machine Company, Windsor, CO). These samples were placed in paper bags, dried in a forced-air oven at 32°C within hours of sampling, and ground with a hammer-mill to pass a 2-mm sieve, followed by analysis for NH_4–N, NO_3–N, and mineralizable N. Analysis of NH_4–N, NO_3–N, and total N was conducted using a Wescan Ammonia Analyzer (Alltech Assoc., Deerfield, IL). After determination of NH_4–N, NO_3–N was converted to NH_4–N using a Zn reduction column and NO_3–N was determined by subtraction from total NH_4–N + NO_3–N. We determined mineralizable N using the phosphate-borate mineralizable nitrogen (PBMN) test described by Gianello and Bremner (1988) as modified by Clay and Malzer (1993). In the fall of 2001 only, the 0- to 60-cm samples were also analyzed for total organic carbon (TOC) and total Kjeldahl N. Total N was determined by wet digestion followed by NH_4–

N analysis. Total organic C was determined using acid pretreatment to remove inorganic C followed by dry combustion (Nelson and Sommers, 1996) and analysis with a LECO carbon analyzer (LECO Corporation, St. Joseph, MI). Soil test values for grid cells which were not sampled in a particular year were estimated using cokriging (Cressie, 1993) in the Spatial Analyst extension of Arc View 9.3 (Environmental Systems Research Inst., Redlands, CA). Cokriging is a geostatistical interpolation technique used to improve prediction estimates for a primary variable by modeling covariance between the primary variable and secondary variables that are sampled more intensively or at different locations. For each cokriging prediction, we used three secondary variables in addition to the primary variable. In all cases, the three secondary variables were measurements of the same soil chemical parameter as the primary variable, but observed in a different year and spatial location. For example, the map of 2003 NH_4–N values was produced using the 2003 NH_4–N sample results as the primary variable and NH_4–N sample results from 2001, 2005, and 2007 as secondary variables. Secondary variables were selected to maximize sampling coverage. To optimize prediction estimates, data that exhibited departure from normality were transformed to approximately normalize the distribution and back-transformed before mapping (Webster and Oliver, 2001). Cross-validation was used to optimize each cokriging model for maximum accuracy and minimum bias (Webster and Oliver, 2001). Soil test values for each 0.014-ha grid cell were extracted as the cell mean from kriged rasters and used for further analysis.

Elevation and position measurements were made on each field using survey grid GPS (horizontal accuracy ± 0.5 m) and land-based laser (vertical accuracy ± 0.05 m). Elevation measurements were made on a semi-regular grid with mean distance between points of approximately 20 m. These coordinates were used to create a digital elevation model (DEM) of the fields using kriging in the Spatial Analyst extension of ArcView 9.3. The DEM raster was used to generate slope, curvature, and aspect rasters using these respective tools in the ArcView Spatial Analyst. The Fill, Flow Direction, and Flow Accumulation tools of the Arc View 9.3 Spatial Analyst extension were used to derive a hydrologic flow accumulation raster for each field. Mean values of the elevation, slope, curvature, aspect, and flow accumulation for each 0.014-ha grid cell of the field were extracted and used in further analysis.

Yield Measurements

In each fall 2002 to 2007, plots were harvested with a modified Model 8 Massey Ferguson plot combine (AGCO Corp., Duluth, GA). This combine was equipped with an electronic ground distance monitor and a computerized HarvestMaster weigh cell (HarvestMaster, Logan, UT). Yield measurements were taken from 15-m sections along selected transects in each field. These 15-m sections corresponded to the 0.014-ha soil sampling grid cells (Fig. 2-1). At the AN site, 330 observations (15 transects of 22 observations) were made each year of soybeans; 594 observations were made for corn in 2002 and 2006, and 792 observations were made in 2004. At the WB site, 345 observations (15 transects of 23 observations) were made of soybean in 2003 and 2005, and 621 observations were made of corn in 2002 and 2004. Harvest observations were more dense on the WB site in 2006 and 2007, with 1196 observations for corn in 2006 and 833 observations for soybean in 2007. For those cells in which corn yield was not measured, yield was predicted based on kriged maps produced from points with the same levels of N and P treatments as the unknown cells. Soybean yield was predicted for unobserved cells using kriged maps produced from all observed points.

Calculation of Phosphorus Removal and Rate of Soil Test Phosphorus Change

Crop removal of P was calculated for each grid cell within each field by multiplying the crop yield for each cell by the predicted grain P concentration based on each cell's STP value, yield, and rate of P applied according to the method described by Anthony et al. (2012), in which STP, yield, and fertilizer P rate are used in a model to predict grain P concentration and P removal. For the 132 cells at site AN and 138 cells at site WB for which we had soil sample results for the length of the experiment, we determined total change in STP over time. We divided the P mass-balance of each grid cell (net of fertilizer P additions and crop P removals) by the change in STP to determine cell-specific values for net kg P addition per 1 mg kg^{-1} increase in STP (+ΔP/ΔSTP) or net kg P removal associated with a 1 mg kg^{-1} decline in STP (–ΔP/ΔSTP). Error in ΔP/ΔSTP was determined by propagating error of prediction for new observations of grain P concentration (Anthony et al., 2012) throughout the calculation of ΔP/ΔSTP according to the standard formula for propagation of error (National Institute of Standards and Technology, 2010).

Statistical Analysis

Statistical analysis was conducted using R version 2.12.1 (R Development Core Team, 2010). Descriptive statistics were determined for soil variables and Pearson's correlation coefficients were calculated between each soil variable within each site-year. Correlation coefficients were also calculated between STP changes and 2001 soil variables and between changes in STP per unit P net addition (removal) and 2001 soil variables. The temporal stability of spatial patterns in soil variables was determined by using the ranked correlation technique (Lamb and Rehm, 2002). Significance of P treatments on STP values over the length of the experiment was tested using a mixed-effects ANOVA model using the R package nlme (Pinheiro et al., 2011), formulated with fertilizer P rate as the fixed effect and with year and main plot as random effects. Comparisons across P treatments were tested using ANOVA models; comparisons across soil variables within P treatments, where the treatment structure was undefined, were tested using the Welch two-sample *t* test. Descriptive relationships between variables were determined using linear and nonlinear regression analysis.

We used geostatistics (Cressie, 1993) to analyze the spatial structure of initial 2001 soil variables and of STP relationship to net P addition or removal. To optimize prediction estimates, data that exhibited departure from normality were transformed to approximately normalize the distribution and back-transformed before mapping (Webster and Oliver, 2001). Sample variograms were calculated and were fitted with exponential, spherical, or Gaussian models using weighted least-squares regression (Cressie, 1993); models were selected to minimize the Akaike information criterion (AIC). Values were estimated for the variogram range, sill, and nugget (Cressie, 1993). Variogram range indicates the separation distance beyond which data no longer exhibit spatial autocorrelation. The proportion of variance in the data attributable to spatial correlation was characterized by the nugget/sill ratio. A lower nugget/sill ratio indicates that a higher percentage of total variance is attributable to spatial autocorrelation. If the nugget/sill ratio was ≤25%, we considered the variable to be strongly spatially dependent; if the ratio was between 25 and 75%, we considered the variable to be moderately spatially dependent; if the ratio was ≥75%, we considered the variable to be weakly spatially dependent (Cambardella et al., 1994). Geostatistical analysis was conducted using the geoR package (Ribeiro and Diggle, 2001) for R version 2.12.1 (R Development Core Team, 2010).

RESULTS AND DISCUSSION

Site Topography and Correlation between Site Variables

At each site, there was a wide range in initial soil chemical variables (Table 2-1), as observed in similar research (Cahn et al., 1994; Kaspar et al., 2004). Mean Olsen STP values fell into the "high" and "very high" categories based on University of Minnesota Extension guidelines at site WB and AN, respectively, but Olsen STP values ranged from the "very low" to "very high" categories at each site (Rehm et al., 2006). All initial soil test potassium (STK) and Zn values at site AN fell into the high and very high categories; at site WB, initial STK and Zn ranged from "medium" to very high. Both fields exhibit the gently sloping swell and swale relief that is characteristic of young glacial plains (Fig. 2-1). United States General Land Office maps from the 1850s indicate that both fields had marshes or wetlands in their northeastern corners, which remained until development of agricultural drainage systems in the 1900s (U.S. General Land Office, 1855, 1858). The locations of these former marshes were associated with the highest soil OM values in the fields, which were 123 and 88 g kg^{-1} at sites AN and WB, respectively. These high OM soils in low-lying areas and low OM eroded knolls account for the negative correlation between elevation and OM which was present at each field (Table 2-2). Organic matter also had negative correlations with slope and with curvature at each field. These relationships between OM and topographical features are similar to those observed by Kaspar et al. (2004) in central Iowa on similar soils. In addition to accumulating OM, the marshes were also responsible for patterns of soil pH. Evaporation from soils on the marsh edges led to deposition of carbonates at the depressional rims (Inskeep and Bloom, 1987; Richardson et al., 1994), creating soils with pH 7.5 to 8.0 in these areas and generating the correlations between low elevation and high pH and between concave topography and high pH that occur at both sites. Soil pH, in turn, strongly affected STP values at these sites. This was primarily due to formation of unavailable calcium phosphates in the high pH soils, as mean pH (6.9 at site AN, 7.3 at site WB) was at the upper pH limit of high P availability at each site, and minimum pH values (5.7 at site AN, 5.9 at site WB) were above the range of significant Fe and Al fixation (Brady and Weil, 2002; Busman et al., 2002). Extremely low Bray P1 STP values were observed in soils with high pH values, indicating the neutralization of the acid used as the P extractant in the Bray P1 test in high pH, calcareous soils (Mallarino, 1997). We observed positive correlation between PBMN values and TOC at site AN, but no correlation between PBMN values and TOC at site WB (Table 2-2), indicating that the PBMN test is not measuring a constant fraction of soil OM. Values of PBMN were correlated with total Kjeldahl N at site AN, but were uncorrelated with total Kjeldahl N at site WB. Results of the Bray P1 and Olsen P soil tests were highly and positively correlated at each site.

Spatial Pattern of Site Variables

Variograms indicated that all 16 variables exhibited spatial structure at each site (Fig. 2-2 and 2-3). Nugget/sill ratios of soil chemical variables were ≤0.41, indicating that 59 to 100% of total variance was spatially dependent, depending on the variable (Table 2-3). Among soil chemical variables, STP, pH, and OM exhibited a very high degree of spatial correlation (>95%) and had ranges >300 m, indicating that these parameters were autocorrelated across the extent of each site. Zinc and NH_4–N exhibited spatial dependence at distances of 100 to 300 m, but sample values exhibited independence beyond this range. Samples of NO_3–N exhibited spatial dependence at a range <100 m and were independent at greater distances. Variograms of K, TOC, total N, and PBMN were site-dependent. All soil chemical variables exhibited spatial structure over distances of tens to hundreds of meters, a spatial scale that is conducive to agronomic management with current large-scale field equipment.

Soil Nitrogen

Between-year correlation coefficients for PBMN were positive and highly significant for all comparisons at both sites (Table 2-4), indicating that the spatial patterns of PBMN were consistent across years. Our results, showing that potential N mineralization is stable over 6 yr, confirms the interpretations of Bundy (2006) and van Schaik (1998), indicating that potential N mineralization values can be used over multi-year timeframes in site-specific N recommendations.

In contrast to PBMN values, inter-year correlations of NO_3–N were site-dependent (Table 2-4). At site AN, between-year correlation coefficients for NO_3–N were positive and highly significant across all site-years, indicating that the spatial patterns of soil NO_3–N were consistent across years. In contrast, at site WB, between-year correlation coefficients for NO_3–N were highly variable. We infer that the difference in the temporal stability of the spatial pattern of soil NO_3–N between the two sites in our study is related primarily to soil drainage. Spatial variation in plant available N is controlled primarily by spatial variation in net N mineralization (Qian and Schoenau, 1995), which in turn is governed by the quantity of potentially mineralizable N and by the rate of mineralization. Effects of soil water on net mineralization are well-established (Cassman and Munns, 1980; Griffin, 2008). At the well-drained AN site, correlations between PBMN and NO_3–N were positive and highly significant in all years (Table 2-5). We interpret the close association between PBMN and soil NO_3–N as an indication that even though PBMN varied across this field, the proportion of organic N mineralized was relatively uniform. This suggests that the factors regulating mineralization were uniform. Dharmakeerthi et al. (2005) found a similar result in a multi-year study of spatial variability in plant available N in southern Ontario. That study reported little spatial variation in soil temperature or soil water, so that variation in mineralizable substrate accounted for variation in plant available N. In contrast, correlations between PBMN and NO_3–N were not significant in any year at the poorly-drained WB site (Table 2-5). The saturated soil conditions often observed at this site suggest that N mineralization may have been severely limited in some locations by excess soil water, although other portions of the N cycle, such as denitrification, could also account for the lack of relationship between PBMN and NO_3–N. The contrasting behavior of these two sites indicates that soil drainage is an important regulator of the temporal consistency of net N mineralization.

Soil Phosphorus

A mixed effects ANOVA model indicated that at both sites, fertilizer P treatments resulted in significant changes ($p < 0.001$) to both Bray P1 and Olsen STP values over the length of the experiment. In plots receiving fertilizer P, we observed a mean increase in Olsen STP of 1.9 and 0.01 mg kg^{-1} yr^{-1} at site AN and WB, respectively; in plots receiving no fertilizer P, we observed a mean decrease in Olsen STP of 0.9 and 0.2 mg kg^{-1} yr^{-1} at site AN and WB, respectively. In plots that did not receive fertilizer P additions, the observed decline in STP values from 2001 until the end of the experiment (Δ Olsen STP) was significantly correlated with initial (2001) STP values at both sites (Table 2-6). Declines in STP were greatest for those locations having the highest initial STP values; declines were minimal for those locations having the lowest initial STP values (Fig. 2-4). This observation agrees with those of Dodd and Mallarino (2005, Eghball et al. (2003), Randall et al. (1997) and Webb et al. (1992). These four studies also indicated that with fertilizer P additions, STP increases are greater for sites having lower initial STP values. We observed this pattern at site WB, where the magnitude of STP increase (Δ Olsen STP) was inversely related to initial STP values (Table 2-6). However, we observed no significant correlation between initial STP and STP increases at site AN. At both sites, we observed a significant correlation between STP increases and PBMN, suggesting that this test may relate to potential mineralization of P and that mineralized P contributes to changes in STP.

We found significant relationships between STP changes and net P addition or removal at each site for both Olsen (Fig. 2-5) and Bray P1 STP results. Across fertilizer P treatments, an average of 6.2 and 7.6 kg net P removal or addition was required to change the Bray P1 STP by 1 mg kg^{-1} at site AN and WB, respectively. These values are comparable to values of 5.9 to 6.3 kg P ha^{-1} reported for high and very high testing soils in Iowa by Voss (1987) and to values of 7.6 to 9.3 kg P ha^{-1} reported for Illinois by Peck et al. (1971), but below the value reported by Barber (1979) for Indiana of 15.5 kg P ha^{-1}. While the changes in Bray P1 STP values from our study are useful for comparisons with other work, 40% of soil samples at site AN and 57% of soil samples at site WB tested above pH 7.4, which is the recommended upper limit for use of the Bray P1 test (Frank et al., 1998; Rehm and Schmitt, 1993). Due to the limitations of the Bray P1 test on high pH calcareous soils and the accuracy of the Olsen test across both alkaline and acid soils (Mallarino, 1997; Smyth and Sanchez, 1982), we used only Olsen STP values in further analysis. At both sites, net P addition per unit increase in Olsen STP was significantly different from net P removal per unit decrease in Olsen STP (Table 2-7). Net P removals per 1 mg kg^{-1} decline in Olsen STP ($-\Delta P/\Delta STP$) averaged 25.7 and 32.0 kg ha^{-1} at sites

AN and WB, respectively, which was significantly higher than net P additions per 1 mg kg^{-1} increase in Olsen STP (+ΔP/ΔSTP), which were 3.6 and 8.0 kg ha^{-1} at sites AN and WB. This STP behavior, in which P additions required to raise STP are substantially different than P removals required to lower STP, is similar to relationships observed in Iowa by Prater (2007) and Voss (1987). Such behavior could possibly be attributed to several factors, including the contribution of P that enters the soil through weathering, the labile nature of fertilizer P and its disproportionate contribution to that part of total soil P which is measured by soil P tests (Hedley and McLaughlin, 2005), and the hysteresis observed in P sorption–desorption (Okajima et al., 1983). Prediction error associated with our calculation of P removal ranged from 0.8 to 1.3 kg P ha^{-1} yr^{-1}, with a mean prediction error of 1.05 kg P ha^{-1} yr^{-1}. Propagation of prediction error throughout our calculations resulted in a mean relative error in ΔP/ΔSTP of 0.17 at site AN and 0.11 at site WB.

At both sites, values for ΔP/ΔSTP exhibited consistent spatial structure (Fig. 2-6, Table 2-8). Values for the nugget/sill ratio indicated that 40 to 80% of total variance was spatially dependent, and model variogram ranges were consistent across treatments within sites (Table 2-8). The observed spatial structure of the data indicates that variation in ΔP/ΔSTP is a well-defined spatial attribute at each site, and suggests that ΔP/ΔSTP is related to other site-specific variables and could be managed through site-specific techniques.

We observed significant correlation between –ΔP/ΔSTP and several soil variables at both sites (Table 2-9). Stepwise ANOVA indicated that differences in –ΔP/ΔSTP were most closely related to initial STP values and that other variables were not significant after accounting for differences in initial STP. We previously noted that STP decline rates were strongly correlated with initial STP values. Because –ΔP/ΔSTP accounts for differences in crop removal of P, the correlation between –ΔP/ΔSTP and initial STP indicates that soil chemical processes contribute to higher –ΔP/ΔSTP values at low values of initial STP. When STP is low, there is little labile P in the soil and much higher amounts of P must be removed to have an impact on STP values (Fig. 2-7).

At both sites, $+\Delta P/\Delta STP$ was significantly correlated with pH, PBMN, and initial STP (Table 2-9). Stepwise ANOVA indicated that at site WB, $+\Delta P/\Delta STP$ was most related to soil pH and that other variables were not significant after accounting for pH differences. At site AN, $+\Delta P/\Delta STP$ was related to pH, PBMN, and initial STP. After accounting for these three variables, other variables were not significant at site AN. At pH values of 7.4 and above, $+\Delta P/\Delta STP$ was 1.6 and 3.6 times higher than for pH values below 7.4 at sites WB and AN (Fig. 2-8, Table 2-7). This observation agrees with well-described behavior of P fixation in high pH, calcareous soil (Brady and Weil, 2002). At site AN, $+\Delta P/\Delta STP$ was also related to PBMN (Table 2-9). Values of $+\Delta P/\Delta STP$ were consistently low for PBMN values >325 kg N ha^{-1}, and on average 3.5 times higher for PBMN values <325 kg N ha^{-1} (Fig. 2-8, Table 2-7). We found a negative relationship between $+\Delta P/\Delta STP$ and initial STP at site AN (Tables 2-7 and 2-9). In soils with lower initial STP values, 3.8 times more P was required to raise STP by 1 mg kg^{-1} (Tables 2-7 and 2-9). This result may seem to contrast with those of many long-term P studies, which have often reported higher initial STP values to be associated with higher maintenance P rates (Dodd and Mallarino, 2005; Webb et al., 1992) and smaller increases in STP per unit of fertilizer P addition (Randall et al., 1997). This contrast could be accounted for by greater crop removals of P in high-STP soils. The negative correlation between $+\Delta P/\Delta STP$ and initial STP which we observed is consistent with the general understanding of P buffering capacity in soils, in which lower STP values are associated with higher buffering capacity and higher resistance to STP changes (Kovar and Claassen, 2005).

CONCLUSIONS

Two findings of this research have implications for fertilizer management. First, the spatial pattern of potential mineralizable N was consistent across all 6 yr of this experiment at each site, but the relationship between potential mineralizable N and inorganic N was site-dependent. When indices of potential mineralization are used in development of variable-rate N application maps, potential spatial variability in soil water and other factors that affect the rate of mineralization must also be taken into account. When moisture conditions regulating mineralization rate are relatively uniform, we find reason to expect that the relative spatial pattern of soil-supplied N may be consistent across years, increasing the likelihood of success for predictive site-specific N management.

Second, we observed significant variation across each site in the net P addition or removal per unit change in STP, and this variation exhibited distinct spatial structure. The amount of net P required to raise STP by 1 mg kg^{-1} was up to 350% greater in soils with more alkaline pH values or with lower mineralization values. These differences are large enough to substantially affect the fertilization rates needed to achieve critical STP values and should be accounted for in fertilizer P rate decisions and in economic calculations of site-specific optimum STP values. Knowledge of soil pH, mineralization, and soil buffering capacity can assist farmers in calibrating site-specific fertilizer P application rates needed to raise STP. Additional work to refine procedures for efficient estimation of P mineralization, sorption, and fixation would be valuable to producers seeking to optimize P management.

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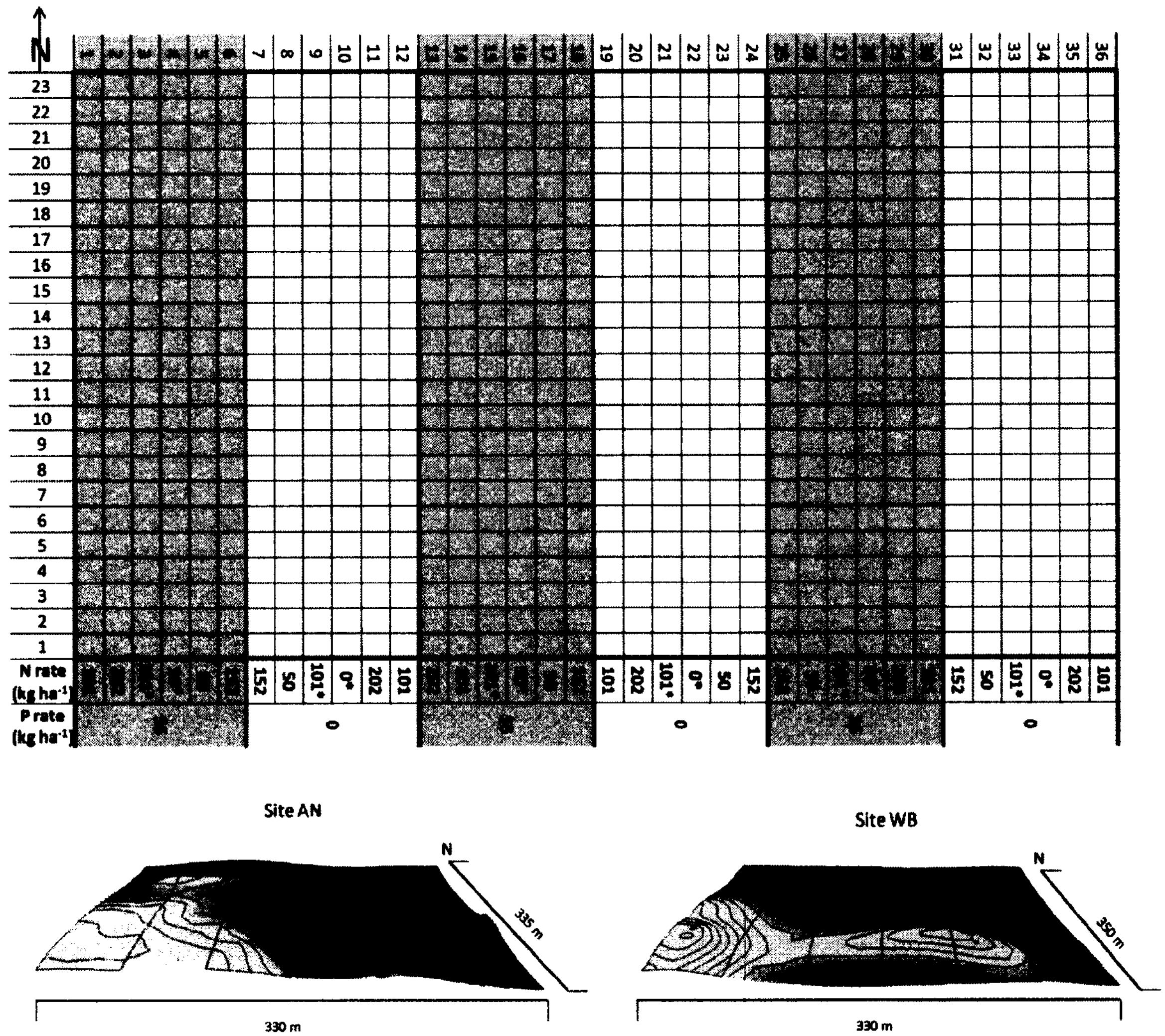

Fig. 2-1. Scheme of experimental design (top) and (bottom left) design imposed on field topography at site AN and (bottom right) site WB. The design consisted of three blocks of two P treatments: with P fertilizer (56 kg ha^{-1}, gray) and no P fertilizer (white). Nitrogen treatments were placed North–South within each P treatment at the rates shown along the bottom of the schematic. Nitrogen rates distinguished with an asterisk alternated in placement every other year to better-maintain a true-zero N rate. Yield and soil observations correspond with each cell in the grid. (bottom) For field topography, elevation is shown with 1-m isolines (black). The vertical dimension is exaggerated by a factor of five for visual clarity. Fertilizer P treatment blocks are outlined in the topography maps with gray polygon.

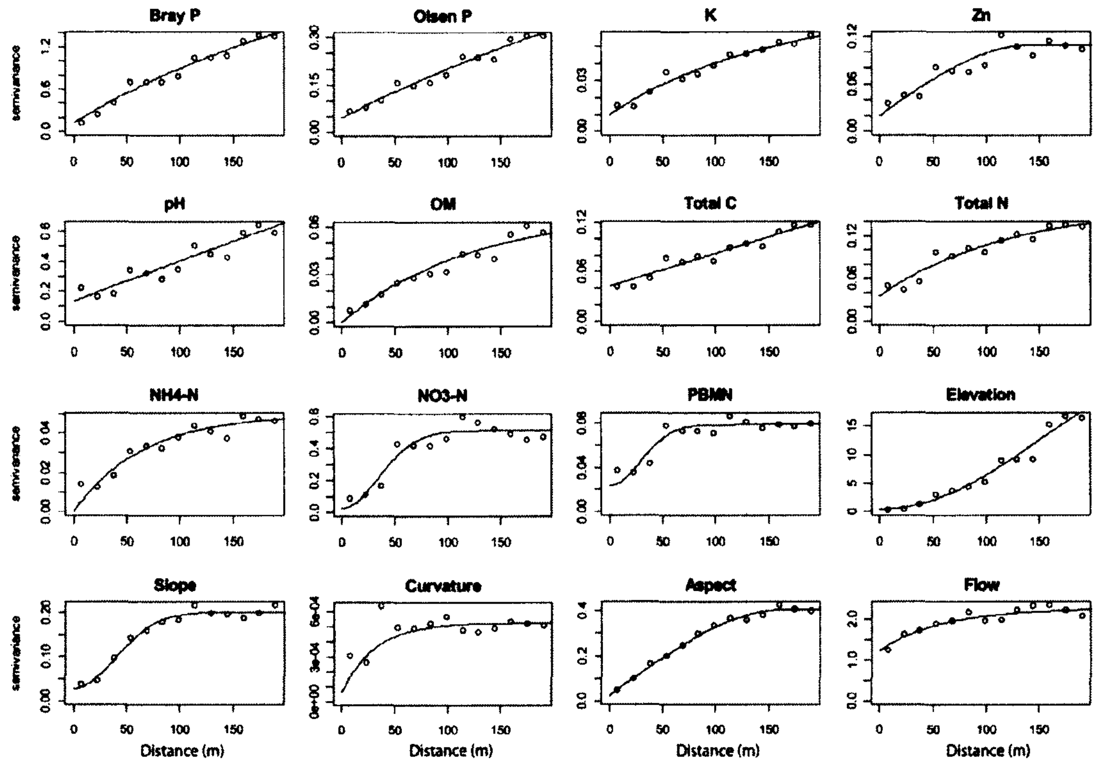

Fig. 2-2. Sample variograms and variogram models for soil and topographical data for site AN at initiation of experiment in 2001.

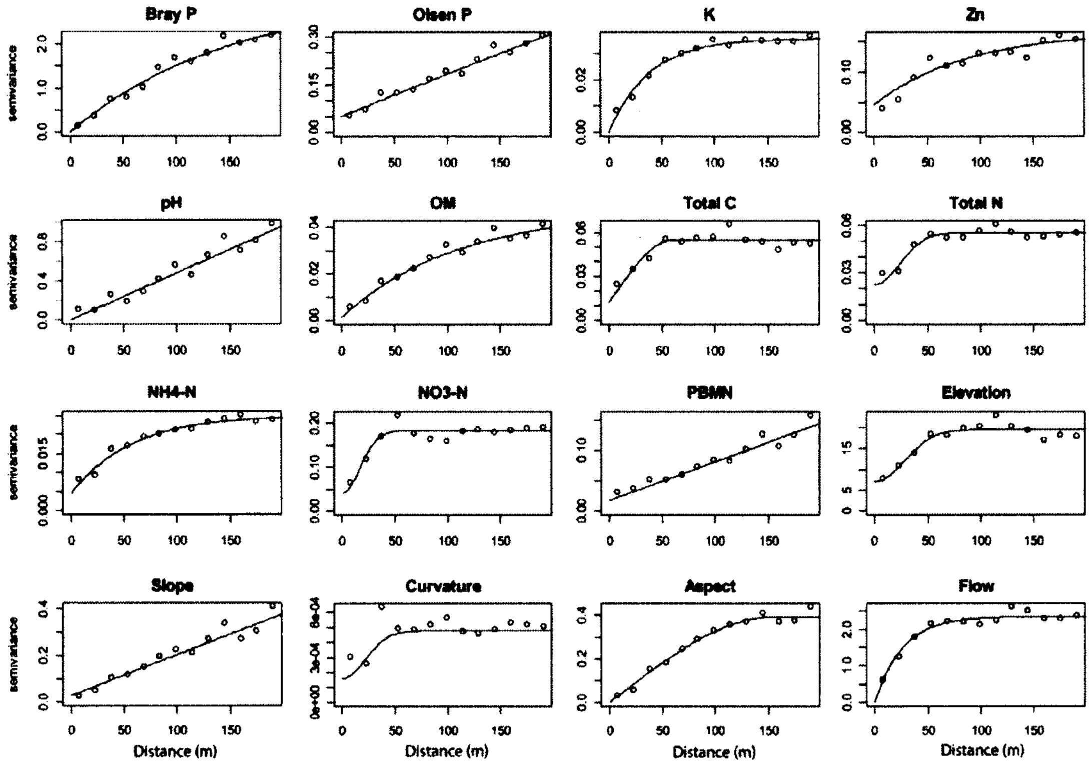

Fig. 2-3. Sample variograms and variogram models for soil and topographical data for site WB at initiation of experiment in 2001.

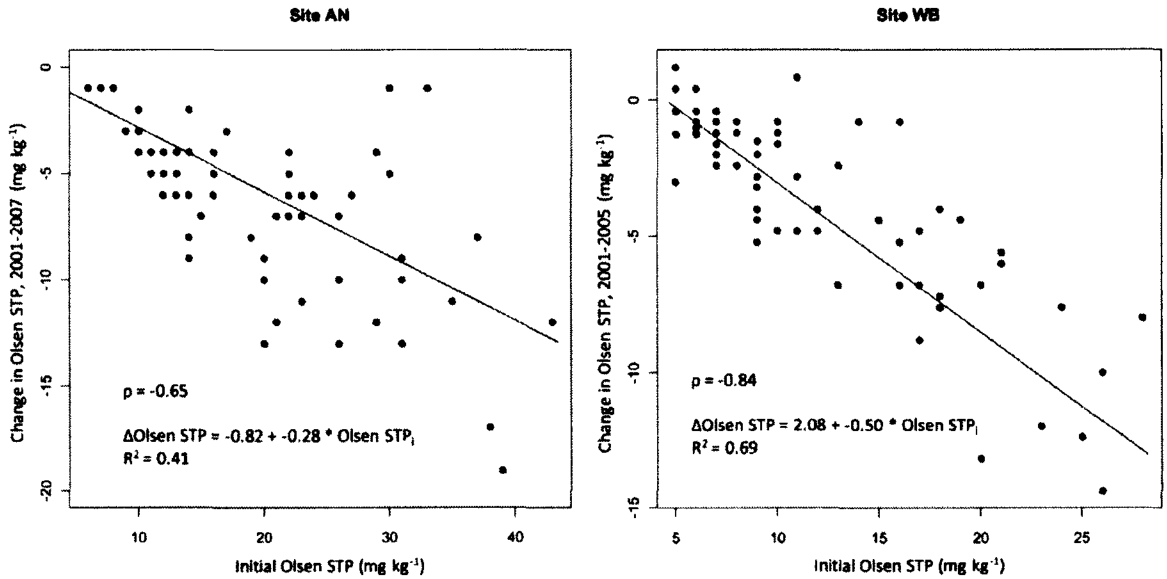

Fig. 2-4. Change in Olsen soil test phosphorus (Δ Olsen STP) over length of experiment and initial 2001 Olsen STP (Olsen STP_i) values in treatments receiving no P fertilizer. At both sites, declines were proportional to initial STP values. Values for Pearson's correlation coefficient (ρ) and *t* tests for linear association were significant at $p < 0.001$ for each site.

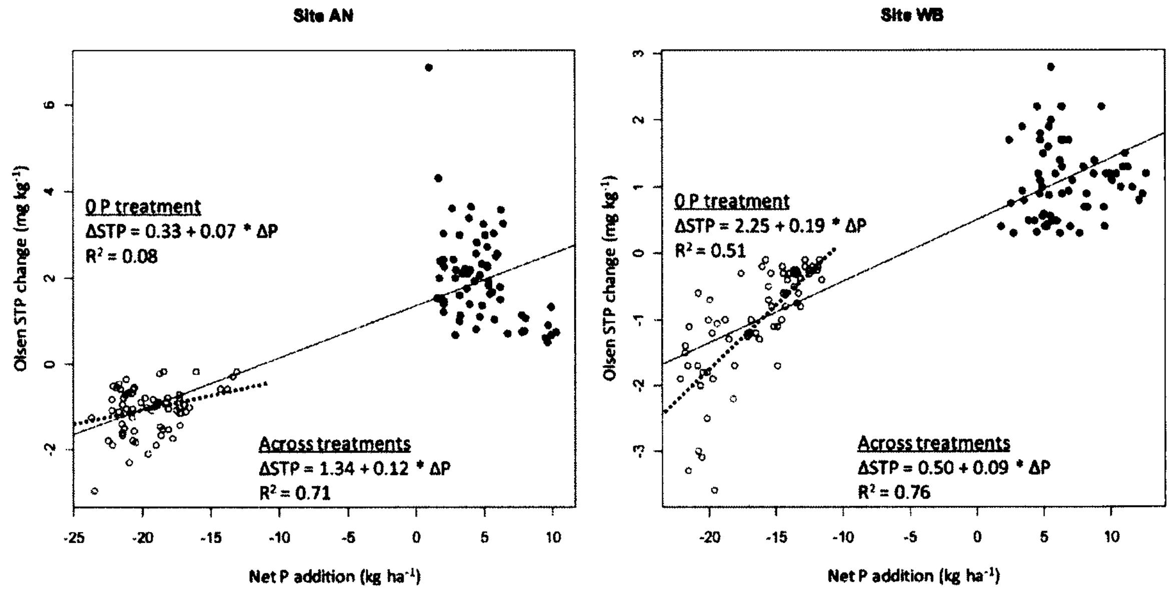

Fig. 2-5. Relationships between mean annual changes in Olsen soil test phosphorus (ΔSTP) and net of fertilizer P additions and crop P removals (ΔP) by site. Open circles are data from plots not receiving additions of fertilizer P; filled circles are data from plots that did receive fertilizer P. Solid linesndicate line of best fit for significant relationships ($p < 0.05$) between net P addition and Olsen STP change across treatments within sites; regression fit is given at bottom of each plot. Mean net P addition per unit change in Olsen STP across treatments can be calculated as the inverse of the slope, resulting in 8.3 kg P per unit change in Olsen STP at site AN, and 10.8 kg P per unit change in Olsen STP at site WB. At each site, we also observed a significant linear relationship ($p < 0.05$) between net P removal and Olsen STP change within the treatment receiving no fertilizer P (dashed line); regression fit is given at top left of each plot.

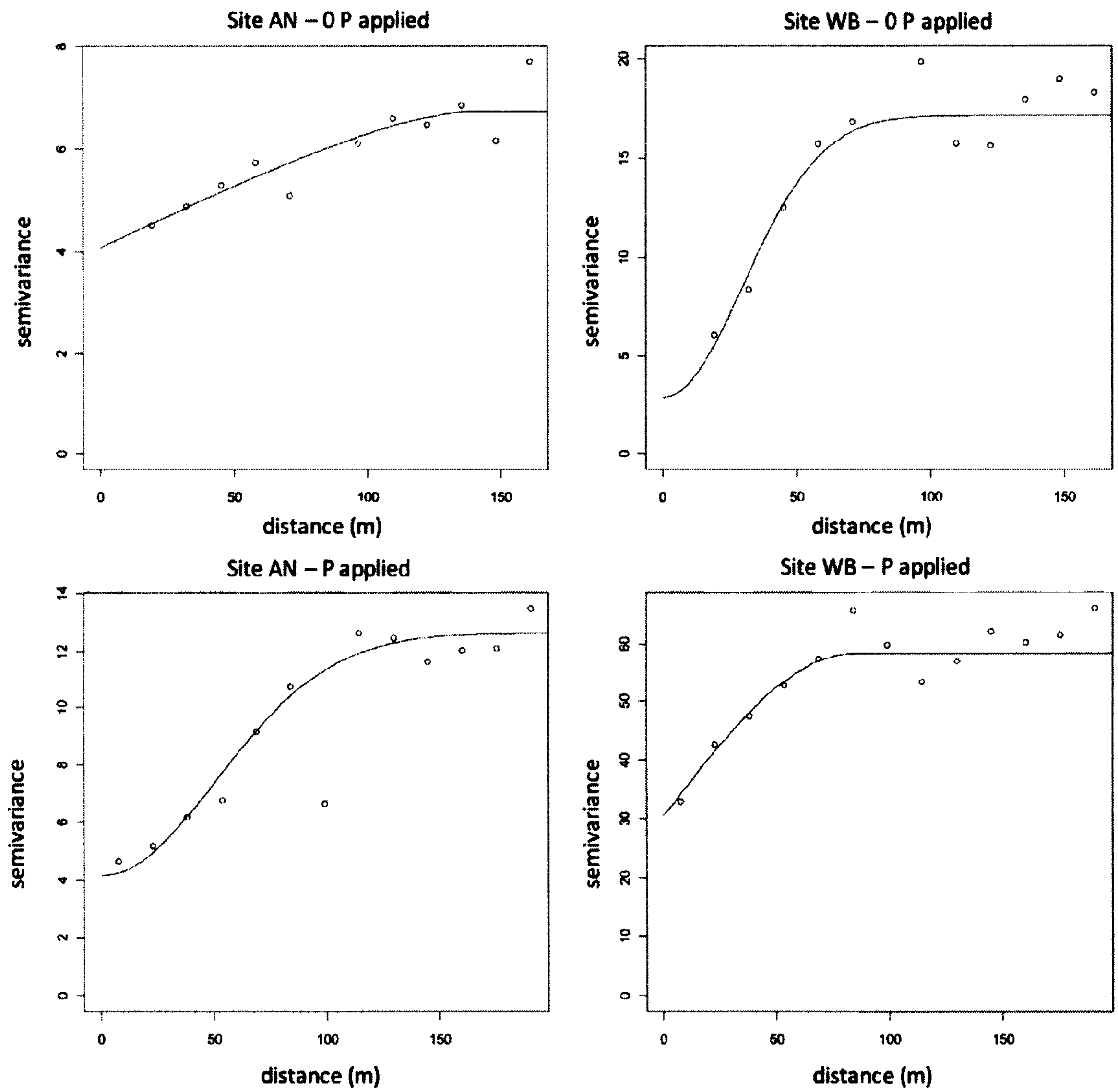

Fig. 2-6. Sample variograms and variogram models for changes in soil test P per unit net addition or removal of P.

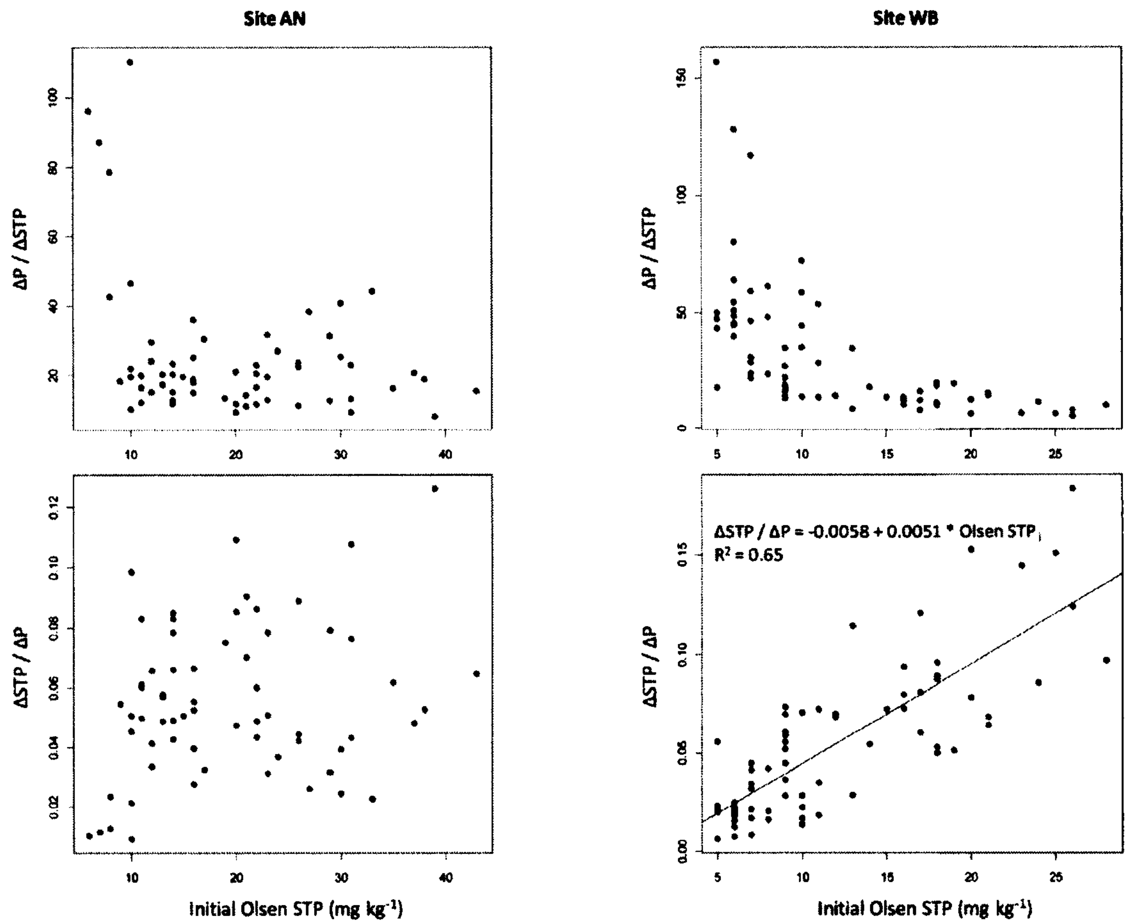

Fig. 2-7. Relationships between net removal of P per 1 mg kg^{-1} change in Olsen STP ($\Delta P/\Delta STP$) and initial Olsen STP values by site. (top row) At both sites, low initial Olsen STP values were associated with large net P removals per 1 mg kg^{-1} reduction in Olsen STP. (bottom row) Transformation of data to $\Delta STP/\Delta P$ resulted in linearization. At site WB, a significant linear relationship existed between $\Delta STP/\Delta P$ and initial Olsen STP; at site AN, this relationship was not significant at $p < 0.05$.

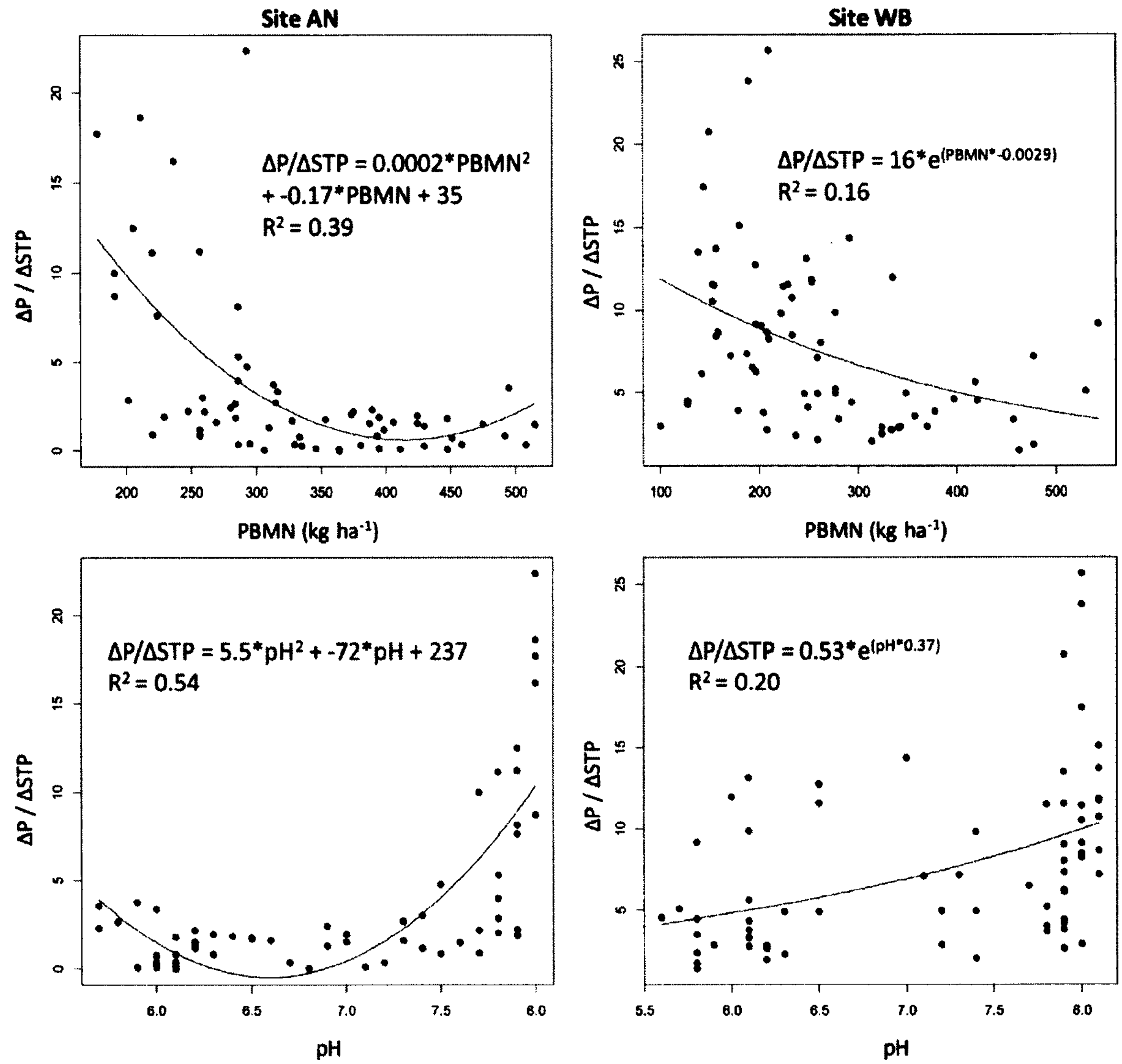

Fig. 2-8. Relationships between the amount of P addition required to raise soil test phosphorus (STP) by 1 mg kg^{-1} ($\Delta P/\Delta STP$) and (top row) phosphate-borate mineralizable nitrogen (PBMN) and (bottom row) pH by site. We observed significant nonlinear relationships between these soil variables and $\Delta P/\Delta STP$. Best-fit regression equations are given in each plot; regression line is shown in black.

Table 2-1. Mean, minimum, and maximum values and standard deviation for 16 soil and topographical variables for intial 2001 sampling at each site.

Site	AN†				WB			
Variable	Mean	Min	Max	SD	Mean	Min	Max	SD
Bray P1, mg kg^{-1}	28	1	93	19	15	1	59	14
Olsen P, mg kg^{-1}	21	5	60	11	13	4	34	7
K, mg kg^{-1}	206	134	400	51	160	107	296	31
Zn, mg kg^{-1}	2.6	1.0	6.9	0.9	1.3	0.6	3.4	0.6
pH	6.9	5.6	8.0	0.76	7.2	5.5	8.1	0.89
OM, g kg^{-1}	68.7	43.0	123.0	16.8	59.2	33.0	88.0	11.3
Total organic C, kg ha^{-1} (× 1000)	228	114	851	106	194	106	343	44.7
Total N, kg ha^{-1} (× 1000)	19.3	9.0	75.1	10.3	17.7	8.5	33.3	4.2
NH_4–N, kg ha^{-1}	64	43	197	17	70	47	102	10
NO_3–N, kg ha^{-1}	43	6	336	46	31	6	88	12
Phosphate-borate mineralizble N, kg ha^{-1}	340	178	683	100	253	100	542	97
Elevation, m above lowest point	8.0	0	15.5	4.0	6.2	0	17.1	4.2
Slope, $\Delta Y/\Delta X$	1.1	0.3	3.1	0.6	1.1	0.1	3.0	0.5
Curvature	0.00	−0.04	0.12	0.02	0.00	−0.06	0.08	0.03
Aspect, degrees	128	40	336	88	102	29	313	66
Flow accumulation, cells	453	10	11624	1443	601	8	13074	1648

† AN , Nicollet County; WB, Brown County; OM, organic matter.

Table 2-2. Pearson correlation coefficients for 2001 soil chemical and topographical variables by site.†

Site	Variable	Bray P1	Olsen P	K	Zn	pH	OM‡	TOC§	Total N	NH_4–N	NO_3–N	PBMN¶	Elevation	Slope	Curvature	Aspect
AN	Olsen P	0.96														
	K	0.14	0.15													
	Zn	0.42	0.48	0.50												
	pH	−0.70	−0.56	0.05	−0.16											
	OM	−0.49	−0.38	0.12	0.26	0.61										
	TOC	−0.31	−0.18	−0.03	0.32	0.39	0.68									
	Total N	−0.24	−0.14	−0.06	0.32	0.31	0.55	0.91								
	NH_4–N	0.05	0.12	0.18	0.41	0.10	0.34	0.40	0.42							
	NO_3–N	−0.15	−0.05	−0.22	0.22	0.13	0.38	0.78	0.84	0.29						
	PBMN	0.30	0.34	−0.09	0.27	−0.22	0.03	0.48	0.60	0.34	0.63					
	Elevation	0.78	0.67	−0.10	0.00	−0.76	−0.74	−0.57	−0.48	−0.19	−0.34	0.10				
	Slope	−0.23	−0.27	0.03	−0.30	0.07	−0.34	−0.24	−0.22	−0.29	−0.25	−0.23	−0.07			
	Curvature	0.17	0.10	−0.01	−0.08	−0.33	−0.35	−0.22	−0.12	−0.15	−0.05	0.15	0.38	0.00		
	Aspect	−0.03	−0.08	0.10	−0.01	0.04	−0.13	−0.07	−0.03	−0.09	−0.16	−0.11	−0.05	0.55	0.10	
	Flow	−0.18	−0.12	−0.12	0.17	0.18	0.39	0.45	0.37	0.15	0.34	0.17	−0.27	−0.16	−0.14	−0.09
WB	Olsen P	0.93														
	K	0.01	−0.10													
	Zn	0.25	0.24	0.46												
	pH	−0.78	−0.76	0.19	−0.14											
	OM	−0.62	−0.49	0.22	0.16	0.64										
	TOC	−0.31	−0.19	0.01	0.16	0.28	0.63									
	Total N	−0.17	−0.12	0.06	0.10	0.14	0.40	0.65								
	NH_4–N	0.23	0.24	0.05	0.23	−0.20	−0.20	0.07	0.13							
	NO_3–N	0.04	0.12	0.03	0.01	0.06	0.22	0.29	0.14	−0.04						
	PBMN	0.70	0.67	−0.16	0.14	−0.79	−0.51	−0.04	0.06	0.21	0.09					
	Elevation	0.75	0.75	−0.41	−0.08	−0.79	−0.72	−0.30	−0.17	0.14	−0.02	0.77				
	Slope	0.60	0.53	−0.29	−0.18	−0.64	−0.64	−0.30	−0.18	0.00	−0.11	0.65	0.72			
	Curvature	0.26	0.30	−0.36	−0.27	−0.20	−0.43	−0.27	−0.21	−0.03	0.10	0.14	0.47	0.27		
	Aspect	0.18	0.18	−0.14	−0.04	−0.34	−0.33	−0.18	−0.02	0.30	−0.04	0.08	0.21	0.02	0.16	
	Flow	−0.06	−0.10	0.33	0.30	0.19	0.18	0.11	0.07	0.11	0.19	−0.19	−0.30	−0.33	−0.14	0.01

† Correlations differ from zero ($p \leq 0.05$) if $\rho > 0.16$.
‡ Organic matter.
§ Total organic carbon.
¶ Phosphate-borate mineralizable nitrogen.

Table 2-3. Parameters of best fitted variogram model for each of 16 soil and topographical variables at initial 2001 soil test levels for each site.

	AN†		WB	
Variable	Nugget/sill	Range	Nugget/sill	Range
		m		m
Bray P1	0.05	>470	0.00	459
Olsen P	0.05	> 470	0.00	>470
K	0.14	457	0.00	114
Zn	0.18	139	0.27	263
pH	0.02	>470	0.00	>470
Organic matter	0.00	365	0.03	325
Total organic C	0.01	>470	0.41	58
Total N	0.22	365	0.23	61
NH_4–N	0.00	193	0.18	172
NO_3–N	0.05	85	0.23	41
Phosphate-borate mineralizable N	0.30	71	0.00	>470
Elevation	0.01	391	0.37	68
Slope	0.14	95	0.00	>470
Curvature	0.17	91	0.40	30
Aspect	0.06	166	0.00	156
Flow	0.55	176	0.00	78

† AN , Nicollet County; WB, Brown County.

Table 2-4. Pearson correlation coefficients for values of phosphate-borate mineralizable nitrogen (PBMN) and soil nitrate N between years for each site.†

Site	Variable	Year	2001	2003	2005
		2003	0.80		
AN‡	PBMN	2005	0.85	0.84	
		2007	0.85	0.94	0.93
		2003	0.74		
AN	NO_3–N	2005	0.83	0.80	
		2007	0.87	0.92	0.94
		2003	0.98		
WB	PBMN	2005	0.95	0.95	
		2007	0.95	0.93	0.97
		2003	–0.11		
WB	NO_3–N	2005	0.22	–0.73	
		2007	0.32	–0.16	0.46

† Correlations differ from zero ($p \leq 0.05$) if $\rho > 0.07$.
‡ AN , Nicollet County; WB, Brown County.

Table 2-5. Pearson correlation coefficients between soil N variables for years 2003, 2005, and 2007 for each site.†

Site	Year	Variable	NH_4–N	NO_3–N
AN	2003	NO_3–N	–0.30	
		PBMN‡	–0.18	0.81
AN	2005	NO_3–N	0.04	
		PBMN	0.39	0.64
AN	2007	NO_3–N	0.32	
		PBMN	0.24	0.74
WB	2003	NO_3–N	0.30	
		PBMN	–0.08	–0.08
WB	2005	NO_3–N	–0.23	
		PBMN	0.21	–0.07
WB	2007	NO_3–N	–0.36	
		PBMN	0.19	0.08

† Correlations differ from zero ($p \leq 0.05$) if $\rho > 0.16$ for 2003 data and if $\rho > 0.12$ for 2005 and 2007 data.

‡ Phosphate-borate mineralizable N.

Table 2-6. Pearson correlation coefficients between initial 2001 site variables and the change in Olsen soil test P over the duration of the experiment by treatment and by site.†

Site‡	Δ Olsen STP by P treatment	Variable	Bray P1	Olsen P	K	Zn	pH	OM§	TOC¶	Total N	NH_4–N	NO_3–N	PBMN#	Elevation	Slope	Curvature	Aspect	Flow
AN	without P fertilizer	Δ Olsen STP	–0.50	–0.58	–0.44	–0.54	0.29	0.13	0.07	0.06	–0.20	0.02	–0.01	–0.05	0.03	0.06	–0.01	0.06
AN	with P fertilizer	Δ Olsen STP	0.10	0.07	0.16	–0.22	–0.16	–0.23	–0.08	–0.06	–0.06	0.16	0.36	0.17	0.10	0.27	–0.10	–0.06
WB	without P fertilizer	Δ Olsen STP	–0.78	–0.83	0.01	–0.13	0.68	0.49	0.19	0.19	–0.39	–0.12	¯0.57	–0.52	–0.39	0.05	–0.39	–0.03
WB	with P fertilizer	Δ Olsen STP	–0.14	–0.21	0.02	0.02	0.00	0.05	–0.01	–0.09	0.09	¯0.12	0.17	–0.07	0.09	–0.18	–0.06	0.04

† Correlations differ from zero ($p \leq 0.05$) if $\rho > 0.16$.
‡ AN , Nicollet County; WB, Brown County.
§ Organic matter.
¶ Total organic carbon.
# Phosphate-borate mineralizable nitrogen.

Table 2-7. Net P addition or removal required to change Olsen soil test phosphorus (STP) by 1 mg kg^{-1} by site, by treatment, and by ranges of soil variables within sites and treatments. For Olsen STP, we chose to divide the categories at 15 mg kg^{-1} based on a typical breakpoint between optimum and high Olsen STP categories (Sawyer et al., 2008). For pH, we chose to divide the categories at a pH of 7.4 based on the recommended upper limit for the Bray P1 test (Frank et al., 1998; Rehm and Schmitt, 1993). For PBMN, we chose to divide the categories at 325 kg ha^{-1} based on an observed inflection point in the data trend.

Site†	Treatment	Mean across treatments	Mean within treatments	PBMN‡ ≤325 kg ha^{-1}	PBMN‡ >325 kg ha^{-1}	pH ≤7.4	pH >7.4	Initial Olsen STP ≤15 mg kg^{-1}	Initial Olsen STP >15 mg kg^{-1}
		kg P ha^{-1}							
AN	0	8.3	25.7***§	23.6	28.1	20.8	33.9***	33.9	20.7***
	56		3.6	5.6	1.6***§	1.9	6.9***	6.9	1.8***
WB	0	10.8	32.0***	37.6	13.6***	16.6	41.9***	42.0	12.0***
	56		8.0	8.7	5.6***	6.1	9.8***	8.5	6.9

*** Significant at the 0.001 probability level.
† AN , Nicollet County; WB, Brown County.
‡ Phosphate-borate mineralizable nitrogen.
§ Significance within this column describes the results of individual pairwise comparison tests of the net P required to change STP by 1 mg kg^{-1} between P treatments. A designated mean is significantly different from the mean immediately below it at the indicated probability level.
§ Significance describes the results of individual pairwise comparison tests of the net P required to change P STP by 1 mg kg^{-1} between ranges of PBMN, pH, and initial Olsen STP values. A designated mean is significantly different from the mean to its immediate left at the indicated probability level.

Table 2-8. Parameters of best fitted variogram model for the spatial pattern of changes in soil test phosphorus (STP) per unit addition or removal of P.

Site†	Treatment	Nugget/sill ratio	Range
			m
WB	0 P	0.17	72.58
WB	P	0.53	81.94
AN	0 P	0.60	137.54
AN	P	0.33	124.90

† AN , Nicollet County; WB, Brown County.

Table 2-9. Pearson correlation coefficients between initial 2001 site variables and net P addition or removal per unit change in Olsen soil test phosphorus (ΔP/ΔSTP).†

Site‡	P treatment	Variable	Bray P1	Olsen P	K	Zn	pH	OM§	TOC¶	Total N	NH_4–N	NO_3–N	PBMN#	Elevation	Slope	Curvature	Aspect	Flow
AN	0	ΔP/ΔSTP	–0.28	–0.26	–0.04	–0.18	0.30	0.14	0.05	0.04	0.10	0.03	–0.04	–0.25	0.07	–0.08	–0.01	–0.03
AN	56	ΔP/ΔSTP	–0.60	–0.57	0.13	–0.01	0.58	0.55	0.24	0.03	0.08	–0.26	–0.54	–0.64	–0.06	–0.22	0.00	0.05
WB	0	ΔP/ΔSTP	–0.58	–0.58	–0.01	–0.17	0.46	0.31	0.01	0.02	–0.28	–0.27	–0.40	–0.36	–0.26	0.18	–0.24	0.00
WB	56	ΔP/ΔSTP	–0.27	–0.17	0.10	–0.10	0.36	0.36	0.19	0.27	–0.12	0.16	–0.35	–0.26	–0.35	–0.10	–0.10	–0.03

† Correlations differ from zero ($p \leq 0.05$) if $\rho > 0.16$.
‡ AN , Nicollet County; WB, Brown County.
§ Organic matter.
¶ Total organic carbon.
# Phosphate-borate mineralizable nitrogen.

CHAPTER 3: Soybean Yield and Quality in Relation to Soil Properties[1]

ABSTRACT

To optimize management, farmers require quantitative understanding of the factors affecting variability in soybean [*Glycine max* (L.) Merr.] seed yield and quality. Our objectives were to characterize spatial variation in soybean seed yield, oil concentration, and protein concentration in two south-central Minnesota fields over 6 yr of a corn [*Zea mays* L.]–soybean rotation, and to determine the influence of fertilizer treatments, soil chemical properties, and topography on soybean yield, oil, and protein. Soil and topographical variables were observed on 0.014-ha cells, and included Bray P1, Olsen P, K, Zn, pH, organic matter, total organic C, NH_4–N, NO_3–N, total N, mineralizable N, elevation, slope, curvature, flow accumulation, and aspect. Soybean yields consistently exhibited spatial structure. Within fields, spatial patterns of soybean yields were highly correlated across years, and we observed consistent relationships between yield and soil variables. Overall, soybean yield related positively to soil P and Zn and negatively to pH at all site-years. Models of soybean yield in relation to soil P and Zn indicate that in high pH soils at these sites, yield is optimized when soil P and Zn levels are higher than current extension recommendations. Protein and oil concentrations exhibited inconsistent spatial structure, and the spatial pattern of protein and oil concentrations differed across years. Relationships between soybean quality and soil properties were more consistent between sites within years than across years within sites, indicating that soybean quality is influenced by soil–climate interactions that function on a regional basis.

Abbreviations: CCA, canonical correlation analysis; CV, coefficient of variation; FA, factor analysis; IDC, iron deficiency chlorosis; OM, organic matter; PBMN,

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phosphate borate mineralizable nitrogen; PCA, principal component analysis; STP, soil test phosphorus.

INTRODUCTION

The recent and rapid increase in the capacity to generate, process, and analyze quantitative geospatial information on crops and soils has opened a new opportunity to refine crop and soil management. Rising prices for crops, fertilizer, and land have increased the economic incentive to optimize management for the unique set of soil and environmental conditions that exist at each point within agricultural crop fields. At the same time, end-users are instituting pricing programs that reward soybean producers for delivering crops with high protein and oil concentrations (Brumm and Hurburgh, 2006), creating questions concerning the causes of variability in soybean quality and the potential to increase protein and oil concentration through agronomic management. To optimize soybean production, farmers require quantitative understanding of the relationship between soil properties, agronomic management, soybean yield, and seed quality.

The need for such understanding has been particularly apparent to Minnesota soybean producers in recent years. Farmers in Minnesota have expressed concern about perceived inability to steadily increase soybean yields (Naeve, 2004). In addition, relatively low Minnesota soybean protein concentrations reduce the economic value of the Minnesota soybean crop (Naeve and Huerd, 2008), as protein constitutes a considerable proportion of total soybean value for the end-user (Brumm and Hurburgh, 2006).

Soybean protein and oil concentrations follow a broad geographic trend across the United States, with protein concentrations tending to decrease from the south-east to the north-west (Hurburgh et al., 1990; Brumm and Hurburgh, 2006). Soybean protein concentration has also been shown to be inversely correlated with oil concentration and yield (Burton, 1985; Helms and Orf, 1998; Wilcox, 1998). The degree to which these correlations are related to genotypic or environmental influence is not entirely known (Wilson, 2004), but they are often associated with genotypic variation (Kravchenko and Bullock, 2002; Wilcox and Shibles, 2001). While genotype selection is an important component of crop management, considerable variation in soybean quality also exists within fields planted to single genotypes (Kravchenko and Bullock, 2002). A limited number of studies have reported effects of fertilization on soybean composition (Gaydou and Arrivets, 1983; Haq and Mallarino, 2005; Yin and Vyn, 2003). Reports of the relationship between within-field variation in soybean protein and oil concentration and soil chemical properties are also limited (Bellaloui et al., 2009a).

Soybean yields have also been shown to vary within Minnesota production fields, with yield variation relating to soil test K, carbonate depth, soil water, and slope (Khakural et al., 1998). The applicability of these relationships state-wide across time are not known, and field-scale soybean research from other states suggests such relationships may be highly field and year dependent (Kravchenko and Bullock, 2000; Sawchik and Mallarino, 2008). Previous work has also indicated that optimum P rates vary across Minnesota soybean fields (Lambert et al., 2006), but these results were not quantitatively associated with soil chemical and topographical variables.

Field-scale studies of yield and quality are predicated on measures of crop parameters at a multiple number of discrete spatial locations. These crop response measures are often paired with multiple measures describing site characteristics. Observed site variables in previous field-scale studies of soybean performance have included soil chemical and physical properties (Cox et al., 2003; Sawchik and Mallarino, 2008), topography (Kravchenko and Bullock, 2000; Kravchenko and Bullock, 2002), and geophysical measurements (Kaspar et al., 2004; Martín et al., 2005). Many authors have used the techniques of multivariate analysis to explain crop response based on site characteristics. These techniques have included correlation analysis and multiple linear regression (Garcia-Paredes et al., 2000), principle component analysis (PCA) (Cox et al., 2003), factor analysis (FA) (Kaspar et al., 2004; Sawchik and Mallarino, 2008), and canonical correlation analysis (CCA) (Martín et al., 2005). Authors have regularly observed intercorrelations between site variables (Kaspar et al., 2004; Kravchenko and Bullock, 2000). Use of intercorrelated variables in multiple linear regression is associated with problems in model-fitting and interpretation (Kutner et al., 2005). The relevance of these difficulties to field-scale crop response data has been well described by Martín et al. (2005) and Sawchik and Mallarino (2008). However, other multivariate techniques come with their own sets of difficulties. Principle component analysis creates new, uncorrelated principle components that explain variance in site characteristics, but these principle components may not lend themselves to agronomic interpretation (Sawchik and Mallarino, 2008) and multiple linear regression of the principle components may explain little of the variation in crop yield (Cox et al., 2003; Sawchik and Mallarino, 2008). Latent factors identified through FA may be more suitable than PCA results for agronomic interpretation of soil variability, but may still explain a relatively small portion of crop yield variation (Sawchik and Mallarino, 2008). Instead of maximizing the amount of variation in site characteristics, canonical correlations maximize the association between two groups of variables, and this technique has been used to explain a high proportion of the total variation in crop yield (Martín et al., 2005). However, canonical variables are often interpreted by examining their correlations to the original sets of variables, and this interpretation is subject to the same intercorrelation problems inherent in simple correlation analysis (Johnson and Wichern, 1998). Multivariate analyses have successfully described patterns in soybean yield and quality and associations with soil variables, and have resulted in general recommendations for improving field management (Kaspar et al., 2004), but qualitative site-specific production recommendations have not been forthcoming (Martín et al., 2005).

To address the need for better understanding of causes of variation in soybean yield and quality, we established a multi-year field study at two sites in southern Minnesota. We set out with three objectives: first, to characterize soybean yield, protein, and oil concentration and their variability within fields, between sites, and across multiple years and a range of N and P fertilizer treatments; second, to identify those soil characteristics and fertilizer treatment effects that are most involved in soybean yield and quality; third, to identify quantitative site-specific production recommendations to optimize soybean production.

MATERIALS AND METHODS

Site Description

Field trials were established in the fall of 2001 on two 16-ha fields in south-central Minnesota. The two fields are located in Nicollet County (AN site, 44°23′ N, 94°08′ W) and Brown County (WB site, 44°08′ N, 94°41′ W). The sites were initially developed for agriculture in the 1860s, and have been in a corn–soybean rotation since the 1960s. We chose sites without a history of manure application within the 5 yr before initiation of the experiment to minimize effects of mineralization of residual manure on the soil nutrient and mineralization tests. The soils at the AN site lie within a Clarion–Canisteo–Webster association, and consist of the Canisteo series (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), Harps series (fine-loamy, mixed, superactive, mesic Typic Calciaquolls), Le Sueur series (fine-loamy, mixed, superactive, mesic Aquic Argiudolls), Cordova series (fine-loamy, mixed, superactive, mesic Typic Argiaquolls), Okoboji series (fine, smectitic, mesic Cumulic Vertic Endoaquolls), and Lester series (fine-loamy, mixed, superactive, mesic Mollic Hapludalfs) (Jackson, 1994; USDA-NRCS, 2011). The soils at the WB site lie within a Nicollet–Clarion–Webster association, and consist of the Canisteo series, Clarion series (fine-loamy, mixed, superactive, mesic Typic Hapludolls), Nicollet series (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Okoboji series, and the Fieldon–Canisteo complex (fine-loamy to coarse-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) (Christensen, 1988; USDA-NRCS, 2011). Soils at both sites formed from calcareous glacial till. The AN site is systematically tile drained on 30-m spacings; the WB site has limited tile drainage. Field management is typical for a corn–soybean rotation in south-central Minnesota, and consisted of single-pass fall disk-chisel tillage of corn stubble and single-pass spring field cultivation before soybean planting. Following soybean harvest, fields were chisel plowed. In each soybean year, the farmer planted a single, commercial glyphosate-tolerant soybean variety. At site AN, cultivars were Prairie Brand 2141 RR, Prairie Brand 2183 NRR, and NuTech 7193 SCN/RR; at site WB, cultivars were Croplan 1399 RR, Midwest 1531, and Midwest 2031 in years 2003, 2005, and 2007.

Experimental Design

The fertility experiment included 3 replications of 9 treatments in a split-plot arrangement of a randomized complete-block design (Fig. 3-1). Following common practice, nutrients were applied before the corn year of the corn–soybean rotation. Phosphorus (0 and 56 kg P ha^{-1}) was the main plot; subplots of N treatments (0, 50, 101, 152, and 202 kg N ha^{-1}) were applied in strips across the field, and placement of these strips was randomized within the P treatments. Potassium was applied to the entire field at a rate of 93 kg K ha^{-1}. The K rate and the 56 kg ha^{-1} P rate were selected to meet or exceed anticipated crop removal for the corn–soybean rotation (Sawyer et al., 2008). Because diammonium phosphate (DAP, 18–46–0) was the P source, there was no 0 kg N ha^{-1} treatment within those plots where P was applied. The DAP rate provided N at a rate of 50 kg ha^{-1}. One extra 101 kg N ha^{-1} N strip was included in each main plot to avoid having 0 kg N ha^{-1} treatments repeated on the same strip in consecutive rotations; instead, the 0 kg N ha^{-1} treatments were applied to a strip that had received a 101 kg N ha^{-1} rate in the previous N application. All other treatments were applied to the same strip in each year of application. Identical design was applied at both sites. Nitrogen was applied as anhydrous ammonia (82–0–0) with the nitrification inhibitor nitrapyrin (Dow AgroSciences, Indianapolis, IN), P was applied as DAP, and K was applied as muriate of potash (KCl, 0–0–60) in November 2001 and November 2003. In April 2006, N was applied as anhydrous ammonia without nitrapyrin, P was applied as DAP, and K was applied as muriate of potash.

Yield Measurements

In the falls of 2003, 2005, and 2007, plots were harvested with a modified Model 8 Massey Ferguson plot combine (AGCO Corp., Duluth, GA). This combine was equipped with an electronic ground distance monitor and a computerized HarvestMaster weigh cell (HarvestMaster, Logan, UT). Yield is reported as Mg ha^{-1} on a 13% moisture basis. Yield measurements were taken from 15-m sections along selected 9-m wide transects in each field (Fig. 3-1). To avoid treatment border effects, we harvested a 1.5-m wide strip that was approximately centered in each plot. Transects were selected to obtain data from the 0, 101, and 202 kg N ha^{-1} treatments in the 0 kg P ha^{-1} plots and the 101 and 202 kg N ha^{-1} treatments in the 56 kg P ha^{-1} plots. These treatments were selected to provide data from across the range of residual fertilizer N treatments. Three hundred thirty observations (15 transects of 22 observations) were made each year of soybean at the AN site; at the WB site, 345 observations (15 transects of 23 observations) were made in 2003 and 2005. Harvest observations were more numerous on the WB site in 2007, when 833 harvest observations were collected. However, saturated fall soil conditions at this site-year restricted harvesting to the western two-thirds of the field. Seed samples were retained from each yield measurement and were analyzed for protein and oil concentration using near infrared spectroscopy (NIRS), using a Foss full scanning 6500 monochometer fitted with NIRS equations developed by the University of Minnesota using ISIscan software (Infrasoft Intl., State College, PA) and validated by Caltest (Clifton Park, NY). Protein and oil concentrations are reported on a g kg^{-1} dry weight (0% moisture) basis.

Soil Chemical and Topographical Variables

Soils were sampled in the fall of each year 2001 to 2007. Samples were taken from 9- by 15-m (0.014-ha) grid cells along a subset of the 36 transects of the N plots (Fig. 3-1). Each sample was a composite of six soil cores taken from the center of each grid cell and from points on a circle of 3-m-radius centered in each cell. In the falls of 2001 to 2004, six transects were sampled, totaling 132 samples per year at site AN and 138 samples per year at site WB. In the falls 2005 to 2007, 12 transects were sampled, totaling 264 samples per year at site AN and 276 samples per year at site WB. In the fall of 2001, 0- to 15-cm samples from each cell were analyzed for Bray P1, Olsen P, K, pH, organic matter (OM), and Zn; 0- to 60-cm samples from each cell were analyzed for total organic C, total Kjeldahl N, NH_4–N, NO_3–N, and mineralizable N. In subsequent fall seasons, 0- to 15-cm samples were analyzed for Bray P1, Olsen P, K, and pH. In odd-numbered falls following, which were subsequent to the soybean harvest and preceding the corn year in the rotation, 0- to 60-cm samples were taken and analyzed for NH_4–N, NO_3–N, and mineralizable N. Sampling, handling, preparation, and analysis were conducted according to recommended procedures for the North-Central United States (Brown, 1998; Sawyer et al., 2008). Phosphorus was determined using colorimetric methods on a Brinkmann PC 800 probe colorimeter (Brinkmann Instruments, Westbury, NY). Potassium was determined using a PerkinElmer AAnalyst 100 AA Spectrophotometer (PerkinElmer Corporation, Waltham, MA) set on emission mode at 776 nm. Zinc was determined using an ARL 3560 inductively-coupled plasma atomic emission spectrophotometer (Applied Research Laboratories, Crawley, Sussex, UK). Soil pH and OM were determined according to Brown (1998). Analysis of NH_4–N, NO_3–N, and total N was conducted using a Wescan Ammonia Analyzer (Alltech Assoc., Deerfield, IL). After determination of NH_4–N, NO_3–N was converted to NH_4–N using a Zn reduction column and NO_3–N was determined by subtraction from total NH_4–N + NO_3–N. To determine mineralizable N, we used the phosphate borate mineralizable N (PBMN) test described by Gianello and Bremner (1988) as modified by Clay and Malzer (1993). Total N was determined by wet digestion followed by NH_4–N analysis. Total organic C was determined using acid pretreatment to remove inorganic C followed by dry combustion (Nelson and Sommers, 1996) and analysis with a LECO carbon analyzer (LECO Corporation, St. Joseph, MI). Soil test values for grid cells which were not sampled in a particular year were estimated using cokriging (Cressie, 1993; Webster and

Oliver 2001) in the Spatial Analyst extension of Arc View 9.3 (Environmental Systems Research Inst., Redlands, CA). Soil test values for each 0.014-ha grid cell were extracted as the cell mean from kriged rasters and used for further analysis.

Elevation and position measurements were made on each field using survey grid GPS and land-based laser. Elevation measurements were made on a semi-regular grid with mean distance between points of approximately 20 m. These coordinates were used to create a digital elevation model of the fields using kriging in the Spatial Analyst extension of ArcView 9.3. The DEM raster was used to generate slope, curvature, and aspect rasters using these respective tools in the ArcView Spatial Analyst. The Fill, Flow Direction, and Flow Accumulation tools of the Arc View 9.3 Spatial Analyst extension were used to derive a hydrologic flow accumulation raster for each field. Mean values of the elevation, slope, curvature, aspect, and flow accumulation for each 0.014-ha grid cell of the field were extracted and used in further analysis.

Statistical Analysis

Descriptive statistics and Pearson's correlation coefficients were calculated between each soil variable and soybean yield, protein and oil concentration, and protein/oil ratio. Correlation coefficients were also calculated between soybean yield, protein, and oil concentrations for data collected within each site-year. Significance of fertilizer treatment effects was determined using ANOVA for split-plot, complete block designs. These tests were conducted using R version 2.12.1 (R Development Core Team, 2010)

We used geostatistics to analyze the spatial structure of variability in soybean yield and quality. Sample variograms were calculated and were fitted with spherical and Gaussian variograms using weighted least-squares regression (Cressie, 1993); models were selected through minimization of the Akaike Information Criterion (AIC). Values were estimated for the variogram range, sill, and nugget (Cressie, 1993). Geostatistical analysis was conducted using the geoR package (Ribeiro and Diggle, 2001) for R version

2.12.1 (R Development Core Team, 2010). The temporal stability of spatial patterns in yield and quality was determined by using the ranked correlation technique (Lamb and Rehm, 2002).

Factor analysis was used to group the 16 soil and topography variables into factors. Factors were optimized using a maximum-likelihood algorithm and an oblique factor rotation. Five factors were created for each site-year, based on the ability to sensibly characterize the components of latent factors while maintaining total loadings on each factor that were greater than one. Backward stepwise regression was used to regress soybean seed yield, oil concentration, and protein concentration on the factor scores and all possible two-way interactions between factors. Factors and interactions were retained at $p \leq 0.05$. Analysis and regression followed the example of Sawchik and Mallarino (2008), and were conducted using the factanal and step procedures in R 2.12.1 (R Development Core Team, 2010).

Canonical correlation analysis was used as an alternative method of analyzing associations between site variables and soybean yield and quality. Soybean performance variables were described by vector $\mathbf{p} = (p_1, p_2, p_3)$, and soil variables were described by vector $\mathbf{q} = (q_1, q_2, \ldots q_{16})$. Analysis was conducted following the example of Martín et al. (2005) using the CCA package (Gonzáles et al., 2008) for R 2.12.1 (R Development Core Team, 2010).

Multiple linear regression was used to analyze relationships between a subset of soil chemical properties and soybean yield using the lm procedure in R 2.12.1 (R Development Core Team, 2010). To determine economic optimum levels for various soil chemical properties, we plotted soybean yield against soil test levels and fitted quadratic-plateau response curves using the nls procedure in R 2.12.1 (R Development Core Team, 2010). Economic optimum soil test levels were calculated based on 10 kg P required to raise STP 1 mg kg^{-1} in the absence of crop removal (Anthony et al., 2012), and current prices for fertilizer phosphate (\$1.80 kg P^{-1}) and soybean (\$500 Mg^{-1}). The resulting P/soybean price ratio (0.0036) used in the optimization calculation is similar to historic values for this price ratio. Maintenance rates for P were assumed to be uniform across all

STP values, and the capital costs and returns associated with P application were applied to the succeeding ten soybean crops. While higher maintenance P fertilizer rates may be required for higher STP levels on these soils (Randall et al., 1997), this cost would be offset by returns to higher STP levels beyond the 10-crop timeframe of the analysis.

RESULTS AND DISCUSSION

Soybean Yield and Quality

In all site-years, large within-field variability existed in soybean seed yield, protein concentration, and oil concentration (Table 3-1). Analysis of variance indicated that soybean yield varied significantly by site-year (Table 3-2). Highest yields were obtained in 2007, which was characterized by good growing conditions at these sites and slightly above trend-line soybean yields across Minnesota (USDA-NASS, 2008). The beginning of the growing season was abnormally dry, allowing for good seedbed conditions at planting. May and June precipitation was near normal, providing adequate soil moisture through the middle of the growing season. August was abnormally wet. Temperatures were above normal in May, August, and September, but relatively few days were above 30°C. June and July temperatures were near normal. Solar radiation was above normal. In 2005, soybean yields across Minnesota were above trend-line (USDA-NASS, 2006). Temperatures were above normal for the months of June through September, and daily highs were above 30°C for 6 d in July. Soybean yields in this study were lowest in 2003, and were also below-trend across Minnesota (USDA-NASS, 2004). Mean monthly temperatures were near normal throughout the growing season, but precipitation was below normal from March through September, with a substantial departure below normal in July and August.

Split-plot ANOVA of the fertilizer treatments detected no differences in soybean yield directly related to the N and P fertilizer treatments or their interactions (Table 3-2). The repeated P treatments did have significant effects on soil test phosphorus (STP)

(Anthony et al., 2012). Linear regression of all observed yields in each site-year against fertilizer P rate and STP indicated that soybean yield was significantly related to STP and that fertilizer P treatment was not significant after accounting for the yield–STP relationship. Previous research has demonstrated significant effects on soybean production of P applied before a preceding corn crop (Lambert et al., 2006). Here, all significant soybean yield effects of this residual P were accounted for by STP values measured following the corn year and before the soybean year. The absence of significant fertilizer P treatment effects on soybean yield in the split-plot ANOVA may be attributed to high within-treatment variance in initial STP levels. Because soybean yield response to P rate was not significant after accounting for STP changes resulting from P application, we did not pursue a site-specific crop response function approach such as those proposed for crop response to N applications by Mamo et al. (2003) and Hurley et al. (2004) or for crop response to N and P applications by Lambert et al. (2006).

Soybean oil concentration was the only quality parameter which responded to fertilizer treatments across all years of the experiment (Table 3-2). We observed a significant site × P rate interaction, with higher P rates being associated with slightly higher oil concentrations at site AN, but slightly lower oil concentrations at site WB. Analysis of variance indicated that soybean protein, oil, protein/oil ratio, and protein+oil concentration varied significantly by site and year (Tables 1 and 2). The range of protein and oil concentrations within site-year (mean range = 44 g kg^{-1} protein; 26 g kg^{-1} oil) was substantially greater than regional differences within Minnesota (mean range = 12 g kg^{-1} protein; 9 g kg^{-1} oil) reported by Naeve and Huerd (2008) and was substantially greater than regional differences across the United States (mean range = 17 g kg^{-1} protein; 7 g kg^{-1} oil) reported by Hurburgh et al. (1990), but was similar to the variability reported within Illinois fields (mean range = 81 g kg ^{1} protein; 39 g kg ^{1} oil) by Kravchenko and Bullock (2002). The range of protein and oil concentrations within site-year also equaled or exceeded the ranges reported for commercial soybean lines in North-Central university extension variety trials (Hurburgh et al., 1990; Orf et al., 2010). Mean protein concentration for all site-years was 25 g kg^{-1} lower than the values from a multi-year field study in eastern Illinois reported by Kravchenko and Bullock (2002). This difference is consistent with the generally-observed trend of declining protein concentrations from south-east to north-west in the central United States soybean production area (Hurburgh et al., 1990, Brumm and Hurburgh, 2006). While the minimum protein concentrations we observed were similar to those reported by Kravchenko and Bullock (2002), maximum protein concentrations in the Illinois study were approximately 45 g kg^{-1} higher than the concentrations we observed. Coefficients of variation (CV) for protein concentration in our study were consistently lower than those calculated for the Illinois data reported by Kravchenko and Bullock (2002). Mean oil concentrations for all site-years were approximately 35 g kg^{-1} higher than the Illinois values reported by Kravchenko and Bullock (2002). Differences in minimum oil concentration were most pronounced, with minimum oil concentrations in our experiment 45 g kg^{-1} on average higher than those reported by Kravchenko and Bullock (2002). Mean oil concentrations were highest in 2003. Mean August temperatures were also highest in 2003, which is consistent with research relating oil concentration to mean temperature during seed fill (Naeve and Huerd, 2008). The range of protein+oil that we observed was comparable with the ranges reported by Naeve and Huerd (2008), Kravchenko and Bullock (2002), Hurburgh et al. (1990), and by Brumm and Hurburgh (2006).

Relationships between Yield and Quality

Relationships between soybean yield, protein, and oil concentration differed markedly across years, and between sites in 2003 and 2005 (Fig. 3-2). A significant negative correlation existed between yield and oil concentration at both sites in 2003 and 2005, but in 2007, a weak correlation existed between yield and oil only at site AN (Table 3-3). There was a positive correlation between yield and protein concentration at both sites in 2003 and 2007, but no correlation between yield and protein at either site in 2005. In our experiment, we did not observe the classical negative relationship between soybean yield and protein concentration (Helms and Orf, 1998; Wilcox and Shibles,

2001) and positive relationships between soybean yield and oil concentration (Burton, 1985; Wilcox and Shibles, 2001) when looking across a large number of environments within a select number of genotypes. This suggests that the reported negative yield–protein and positive yield–oil relationships primarily result from genotypic variation, and are not consistently expressed across environments within soybean genotypes. Yin and Vyn (2005) also reported inconsistent relationships between these variables within genotype across environments and years.

We also found a highly significant negative correlation between oil concentration and protein concentration across environments in all site-years (Table 3-3). This correlation was strongest at both sites in 2003. A negative relationship between protein and oil concentration is also widely reported (Helms and Orf, 1998; Wilcox and Shibles, 2001), and is often attributed to genotypic variation (Kravchenko and Bullock, 2002; Wilcox and Shibles, 2001). The presence of a significant, negative correlation between protein concentration and oil concentration within each of the genotypes planted at the six site-years indicates that the negative protein–oil relationship is also related to effects of environmental variability. Although the absolute levels of soybean yield and quality (Table 3-1, Fig. 3-2) differed considerably between sites and across years, the patterns of the relationships between these variables were remarkably consistent between sites within years (Table 3-3). We interpret this consistency between sites within years as evidence that the patterns of the relationships between soybean yield, protein concentration, and oil concentration are driven primarily by weather and climate factors that act on a regional scale, even though the absolute values of these variables are influenced by complex interactions of soil factors, climate, and genotype.

Spatial Patterns of Yield and Quality

Analysis of between-year correlations of the spatial patterns in soybean yield, protein, and oil revealed different behavior, depending on the parameter (Table 3-4). Despite considerable variation in weather patterns across years, the spatial patterns of soybean yield remained consistent across years at each field. Because the spatial patterns of soil chemical and topographical variables were consistent across years, we interpret the temporal stability of spatial yield patterns to indicate that underlying soil physical and chemical properties are significant and substantial components of within-field variability in soybean yield. Better understanding of the nature and mechanisms of these underlying relationships should create opportunities to improve agronomic management. In contrast to yield, inter-year correlations in spatial patterns of protein and oil concentrations and their sum were more erratic. Correlations in the spatial pattern in quality traits were greatest between the 2003 and 2005 growing seasons at each site; correlations between the 2003 and 2007 growing seasons were lowest. This pattern is identical to that found in a correlation analysis of 40 indicators (including monthly mean temperature, monthly extreme temperature, monthly evapotranspiration, monthly precipitation, season growing degree units, solar radiation, and mid-summer soil moisture) of growing season climate between years: the 2003 and 2005 growing seasons were most similar; the 2003 and 2007 growing seasons were least similar (data not shown). The spatial patterns of soybean quality traits appear to be more subject to interaction between climate and soil properties than are the spatial patterns in soybean yield. Of the quality traits, the spatial pattern of the protein/oil ratio was most consistent across years, suggesting that this ratio is more closely associated with underlying soil factors than are protein or oil concentrations alone. Inter-year correlations for protein yield ha^{-1}, oil yield ha^{-1}, and protein+oil yield ha^{-1} were very similar to the yield correlations, indicating that these values are driven primarily by patterns of yield variability.

At each site, sample variograms for soybean yield had a well-defined spatial structure that was consistent across years (Fig. 3-3, Fig. 3-4). The consistency in yield variogram model parameters across years within sites is another indication of the temporal stability of the underlying spatial processes driving soybean yield at each of these sites (Table 3-5). At both sites, the yield variogram nugget/sill ratio was ≤ 0.36, indicating that a high proportion of the total variance in soybean yield could be explained by spatial correlation at distances equal to or exceeding our sampling interval. Variogram model range for soybean yield was consistently greater at site WB, indicating that spatial correlation functioned on a broader scale at this site. In contrast to yield, the sample variograms for protein and oil concentration were less consistent across years. Nugget/sill ratios were generally much higher than those for soybean yield, indicating that a larger proportion of the variability in protein and oil was present at distances shorter than our sampling interval. Variogram model ranges varied substantially across years within sites, although they were usually within the same order of magnitude as the ranges of yield variogram models. Sample variograms for oil concentrations in 2007 are particularly interesting, as they indicate there was no spatial structure to oil concentration in this year at site AN and very little spatial structure at site WB. We interpret this data as additional evidence that underlying soil properties are a relatively less important factor in determining soybean quality characteristics than in determining soybean yield. Parameters for the variogram models of the protein/oil ratio were more consistent across years than those for protein or oil alone, again indicating that the spatial structure of the protein/oil ratio is more stable over time.

Correlation of Yield and Quality with Site Variables

Positive correlations between yield and STP, Zn, and elevation were observed in all site-years (Table 3-6). Yield correlated negatively with pH and OM in all site-years. Soil pH correlated most strongly with yield in three of six site-years, more than any other variable. Soybean plants in high pH areas of each site exhibited visual symptoms of pH-related iron deficiency chlorosis (IDC). The dominant relationship between soil pH and yield reinforces the magnitude of the management challenge imposed by high soil pH and IDC in the Upper Midwest (Hansen et al., 2003). We observed no consistent correlations between yield and soil K, which differs from the results of a similar experiment in Minnesota reported by Khakural et al. (1998). In our experiment, every soil test K value at both sites was >121 mg kg^{-1}, which is the soil test value above which Minnesota extension recommendations advise no fertilizer K for soybean production (Rehm et al., 2001). Our high soil test K values could explain the lack of yield response to soil K.

There were some consistencies between soybean quality and soil variables. Nitrogen mineralization index exhibited significant positive correlation with the protein/oil ratio in four of six site-years (Table 3-6). We observed significant positive correlations between N mineralization index and protein concentration in four of six site-years. This relationship is consistent with reports showing that soybean protein concentrations respond positively to in-season N fertilization (Schmitt et al., 2001). However, protein concentrations were positively related with soil NO_3–N in only two of six site-years. In light of the consistent relationship between N mineralization and the protein/oil ratio, the absence of a consistently positive relationship between soil NO_3–N and soybean protein concentration is not readily explained. We observed significant negative correlations between N mineralization index and oil concentration in five of six site-years. Soil K exhibited significant negative correlations with the protein/oil ratio in all site-years and positive correlations with oil concentration in five of six site-years (Table 3-5). Similar relationships were found by Gaydou and Arrivets (1983), Sale and Campbell (1987), and Yin and Vyn (2003), who reported that fertilizer K treatments result in lower soybean protein concentration and higher soybean oil concentration. The protein/oil ratio correlated more strongly with soil pH than any other soil variable in three of six site-years. In these 3 yr, soil pH was negatively related to the protein/oil ratio. We attribute this relationship to two factors. First, in these 3 yr soybean protein concentration was positively related to soil P. Protein synthesis may have been particularly sensitive to pH-induced P unavailability in these years. Second, we observed plant symptoms of IDC in the high-pH soils at these sites. These symptoms included reduction in canopy height (Hansen et al., 2003) and failure to form a crop canopy between rows. Decreased albedo related to canopy may have resulted in higher air temperatures within the canopy during seed-fill, which have been shown to result in higher soybean oil concentrations (Naeve and Huerd, 2008). However, in the other three site-years, pH was either unrelated (two cases) or was positively related (one case) to the protein/oil ratio. Protein concentration was positively correlated with soil P and was negatively correlated with pH at both sites in 2003, while these relationships were not as strong in other years. Other unobserved factors, such as soil water (Bellaloui and Mengistu, 2008) and maturity–climate interactions (Bellaloui et al., 2009b), have also been shown to influence soybean protein and oil concentrations. In our research, the relative consistency of seed composition–soil variable relationships between sites within years suggests that temporal variations in the spatial structure of soybean protein and oil concentrations are due, in part, to interactions between climate and soil variables that hold true on regional scales.

Factor Analysis

Within sites, soil and topographical variables grouped into easily-identifiable latent factors in a consistent manner across years (Table 3-7). Five factors were retained for each field in each year. At site WB, four of the five latent factors were present in all years. We named these factors *N availability*, *P availability*, *K and Zn availability*, and *residual* NH_4*–N*. In 2003 and 2005, we named the fifth latent factor *mineralization potential and soil pH*; in 2007, we named the fifth latent factor *soil organic matter*. At site AN, four of five latent factors were also present in all years, and these four factors were identical to those identified at the WB site. In 2003 and 2005, the fifth factor present at site AN was named *slope and aspect*; in 2007, we named the fifth latent factor soil *organic matter and pH*. The consistency of latent factors across years within each site was not surprising, as fertilizer treatments, crop removals, and inherent soil processes were the only mechanisms with potential for differential influence on soil properties across years. However, latent factors were also consistent between sites across years, and only two differences in latent factors existed between sites. First, at the poorly-drained WB site, the soil N variables grouped separately from the mineralization index, and mineralization index grouped together with elevation and slope. At the pattern-tiled and well-drained AN site, a single latent factor included both soil N variables and the mineralization index, and include slight, but negative loadings of the elevation and slope variables. We interpret this difference as evidence that at the WB site, poor drainage limited the process of mineralization in soils with high mineralization potential, while at the AN site, good internal drainage allowed for high correlation between mineralization potential and actual N mineralization. Second, since mineralization and N availability grouped together at site AN, there was room for other variables to constitute the fifth latent factor. In 2003 and 2005, this fifth factor was dominated by the topographical variables aspect and slope. In 2007, aspect and slope grouped with residual ammonium, and the fifth latent factor was dominated by organic matter and pH.

The latent factor P availability had negative pH loadings at all site-years, but the negative pH loading had a value <-0.50 at only one site-year, suggesting that P availability was being identified independently of pH effects on P availability. Soil K and Zn grouped together at all site-years except 2007 WB, when Zn grouped with residual NH_4–N. The similarities in latent factors between these sites was not expected, but could be attributed to similarities in the parent material and soil-forming processes.

Stepwise linear regression of soybean yield against latent factors indicated that factors significantly contributing to yield were common across years and between sites. Yield was positively related to latent factors that represented high P availability, high mineralization potential, high K and Zn availability, and low pH. R^2 values for regressions of yield against latent factors ranged from 0.30 to 0.47. Regression of soybean protein and oil concentrations against latent factors showed fewer consistent relationships. At site WB, protein concentration tended to be positively associated with latent factors having positive loadings for mineralization and P availability and negative loadings for pH, while oil concentration tended to be negatively associated with these same variables. At site AN, protein concentration tended to be negatively associated with latent factor K and Zn availability, while oil concentration was positively associated with this latent factor.

Canonical Correlation Analysis

Canonical correlation analysis between the observed variables of the harvested soybean crop and soil and topographical variables produced a total of three pairs of canonical correlations for each site-year. All three canonical correlations were significant ($p < 0.01$, Wilk's Lambda) at all site-years except the AN site in 2007, where only the first two canonical correlations were significant. Results from pooled data across all site-years (Table 3-9) were generally consistent with results from individual site-years (Table 3-8), so we will describe results of the pooled data, highlighting site-year specific variation when needed.

Three significant canonical variables were observed in the pooled transect data. The first canonical variable of the soybean data had a strong negative correlation with yield, and a somewhat weaker positive correlation with oil concentration. The first canonical variable of the soil data had a moderately negative correlation with soil P, a very strongly positive correlation with pH, moderately positive correlations with OM and NH_4–N, and moderately negative correlations with mineralization index, elevation, and slope. The second canonical variable of the soybean data had a positive correlation to oil concentration, a negative correlation to protein concentration, and a positive correlation to yield. The second canonical variable of the soil data had moderately positive correlations to soil P, K, Zn, mineralization index, and NH_4–N. The third canonical variable of the soybean data had a negative correlation to protein concentration. The third canonical variable of the soil data had a positive correlation to soil K and a negative correlation to mineralization index and total N. From these correlations, we derived interpretations of the overall patterns relating soil characteristics to crop performance. Yield was positively related to soil P, Zn, mineralization index, elevation, and slope, while having a strongly negative relationship to pH. Evaluation of individual site-years indicated that the positive relationship between yield and mineralization index was strongest at the WB site and weaker at the AN site, while the positive relationship between yield and slope existed only at the WB site. These results are consistent with the results of the correlation analysis. Overall, protein concentration was positively related to the mineralization index and was negatively related to soil K. In some site-years, protein concentration was also positively related to soil P and negatively related to soil pH. Overall, oil concentration was positively related to soil K. In some site-years, oil concentration was positively related to soil pH and negatively related to soil P and mineralization index.

Similar research has often reported negative correlations between yield and elevation and slope, with higher yields associated with lower, flatter portions of the landscape (Changere and Lal, 1997; Fahnestock et al., 1996; Kravchenko and Bullock, 2000; McConkey et al., 1997). These studies attributed this association to water movement patterns that provided more adequate plant water supplies in flat, low-lying areas of fields. Kaspar et al. (2004) found that the yield-elevation/slope relationship reversed in wet years, during which flat, low-lying areas had excess water, resulting in lower yields. In our experiment, we attribute the positive correlation between elevation and yield to pH effects. At both sites, pH and elevation were strongly correlated, with higher pH areas occurring at lower elevations. Overall, pH was the soil variable most correlated with yield, and this correlation was negative. Slope was positively correlated with yield only at site WB, which we attribute the poor internal drainage at this site.

Critical Soil Nutrient Levels by Zone

The consistency of relationships between soil variables and soybean yield across all site-years suggests that soybean yield may respond consistently over time to zone-specific management. While all soil variables may be modified through management, some, such as soil fertility, are much more easily managed on a short-term basis than others, such as elevation, slope, pH, or mineralization potential. To identify zones, we focused soil pH. Soil pH demonstrated a consistent spatial structure in each field, is relatively easy to measure, and is relatively more difficult to modify than soil nutrient levels. Our factor analysis indicated that pH grouped on different factors than those including soil P and Zn, indicating that both soil P and Zn varied within pH zone. The availability of both P and Zn is strongly influenced by pH (Marschner, 1995), suggesting that zones of different pH may have different optimum levels of P and Zn for soybean yield. For analysis of optimum nutrient levels by pH zone, we grouped soil pH values into three regions: moderately acidic (pH < 6.7); neutral (pH 6.7–7.2), and moderately alkaline (pH > 7.2).

Although the range of observed STP was similar across pH zones, the STP levels at which soybean yields reached an apparent maximum differed considerably across zones (Fig. 3-5). In the moderately acidic soils and neutral soils, soybean yields were maximized at Olsen STP values of 15 and 19 mg kg^{-1}, respectively, which is slightly above the upper limit of the range of current recommendations for optimum STP values for Minnesota (11 mg kg^{-1}, Rehm et al., 2001) and Iowa (14 mg kg^{-1}, Sawyer et al., 2008). In moderately alkaline soils, however, the quadratic-plateau response model indicated that yields reached a maximum at 36 mg kg^{-1} Olsen STP. Although P availability declines as soils become increasingly calcareous (Brady and Weil, 2002), the Olsen STP test is considered to accurately represent crop-available P in alkaline soils (Frank et al., 1998). Using a quadratic-plateau model, our data indicates that with long-term land tenure, economic optimum Olsen STP values are approximately 15 mg kg^{-1} on the moderately acidic and neutral soils, but are approximately 30 mg kg^{-1} in the moderately alkaline, calcareous soils. Data from this study indicates that in moderately alkaline, calcareous soils, soybean yield may be optimized at STP levels considerably above those currently recommended.

Like STP values, the range of observed soil test Zn levels was similar across pH zones. Of all Zn soil values 99.5% were above recommended soil test Zn value for Minnesota (0.75 mg kg^{-1}, Rehm and Schmitt, 1997). We observed no significant change ($p \leq 0.05$) in soybean yield across the range of soil test Zn values in the moderately acidic and neutral soils (Fig. 3-5). In the moderately alkaline soils, we observed an increase in soybean yields across the range of soil test Zn values. Zinc deficiency in soybean has been shown to be pH dependent (Adams et al., 1982; Payne et al., 1986). Deficiencies of

Zn in calcareous, high pH soils result from increased Zn adsorption at high pH and also from bicarbonate inhibition of Zn uptake and translocation (Marschner, 1995). These results indicate that soybean yields may be maximized in moderately alkaline, calcareous soils by soil test Zn levels that are considerably higher than current recommendations.

SUMMARY AND CONCLUSIONS

In the six site-years of this trial, soybean seed yield showed no response to residual N from fertilizer treatments applied to the preceding corn crop. Phosphorus soil tests following the corn crop captured sufficient information on residual fertilizer P to describe the significant soybean yield response to P which we observed. Soybean yield demonstrated a consistent spatial structure within each field, and the spatial pattern of yield was consistent within sites across years.

Protein and oil concentrations varied widely within fields in each year of this study. The range of this variation exceeded regional differences in protein and oil concentration. Relationships between yield, protein concentration, and oil concentration differed across years, but demonstrated consistency between sites within years, indicating that regional climate and weather patterns have a strong influence on these relationships. In most years, protein and oil concentrations had a spatial structure. However, the spatial patterns of protein and oil concentration showed less consistency within sites across years, and were often uncorrelated between years. Total protein and oil yield were driven primarily by the total volume of soybean produced. Protein/oil ratio demonstrated a consistent positive relationship to the soil mineralization index and a negative relationship to soil test K. In some years the protein/oil ratio exhibited a significant negative relationship to soil pH. Overall, relationships between soybean quality and soil variables were more consistent between sites within years than within sites across years, indicating that soybean quality is affected by climate–soil interactions that operate on regional scales. These results confirm previous findings indicating that producers have some ability to manipulate soybean quality through soil K management, and that soil N mineralization and pH may also influence soybean protein and oil concentrations. However, the effect of these soil chemical factors on soybean quality may change with inter-annual variation in regional climate.

The soil and topographical variables most strongly associated with soybean yield were consistent across sites and years. Yield was most strongly associated with soil pH, with yields being consistently lower in areas of high pH. This provides additional evidence that pH-related IDC is the most significant soil chemistry-related management problem in the glacial-till soils of the North-Central United States. In moderately acidic and neutral soils, soybean yield was optimized at a STP level of $\approx$15 mg kg^{-1} and was not responsive to Zn, which agrees with current recommendations for the North-Central United States. In moderately alkaline soils, soybean yield was optimized at STP values $\approx$30 mg kg^{-1} and soil test Zn values > 5 mg kg^{-1}. While these results are observational, their consistency across sites and years suggests that experimental work to confirm these results could lead to improvements in site-specific soybean production management.

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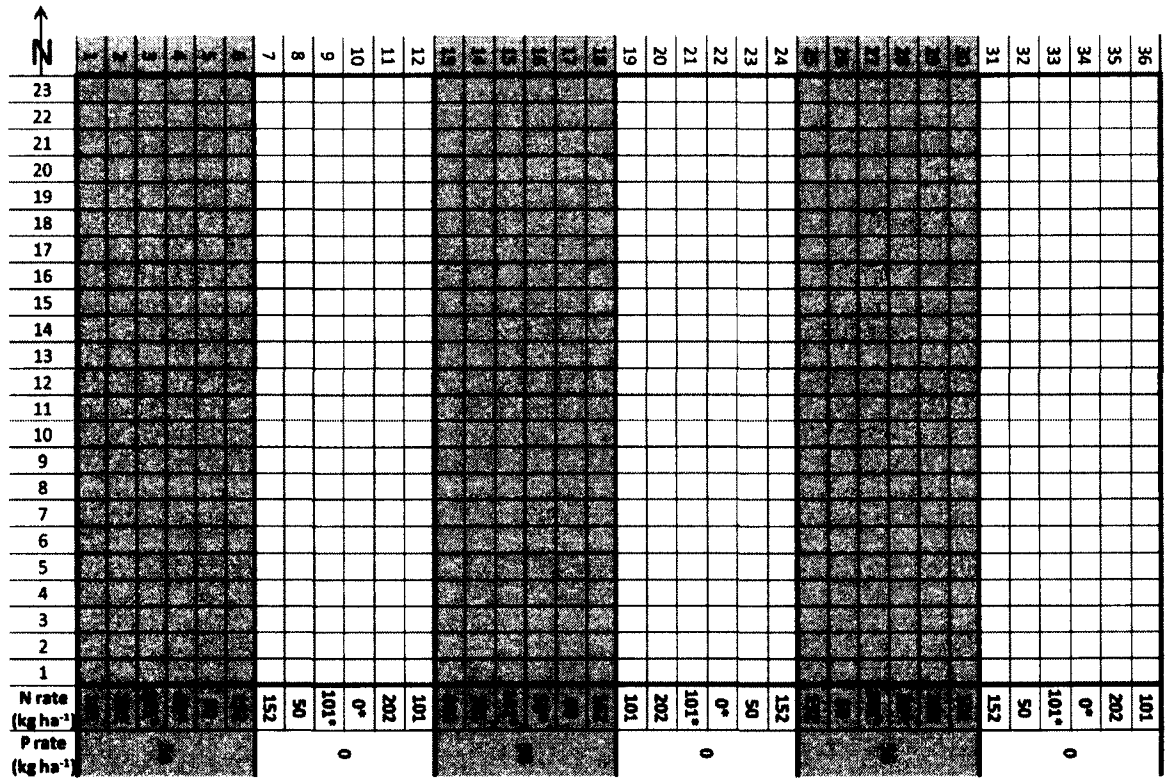

Fig. 3-1. Scheme of experimental design. The design consisted of three blocks of two P treatments: with P fertilizer (56 kg ha^{-1}, gray) and no P fertilizer (white). Nitrogen treatments, applied to corn, were placed N–S within each P treatment at the rates shown along the bottom of the schematic. Nitrogen rates distinguished with an asterisk alternated in placement every other rotation to better-maintain a true-zero N rate. Yield and soil observations correspond with each 15-m (N–S) by 9-m (E–W) cell in the grid.

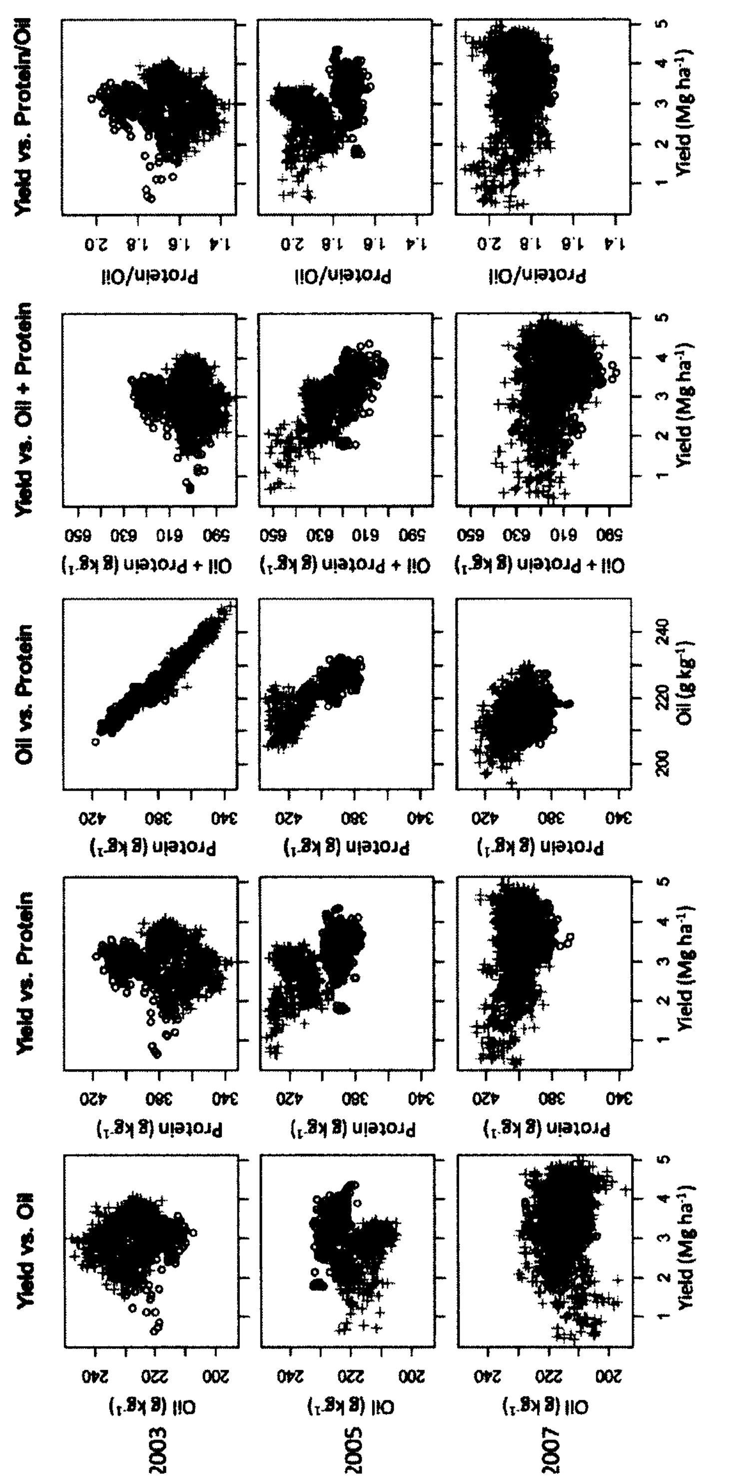

Fig. 3-2. Plot of relationships between soybean yield, oil concentration, protein concentration, oil + protein concentration, and protein/oil ratio by year and site (site AN in black circles, site WB in gray crosses).

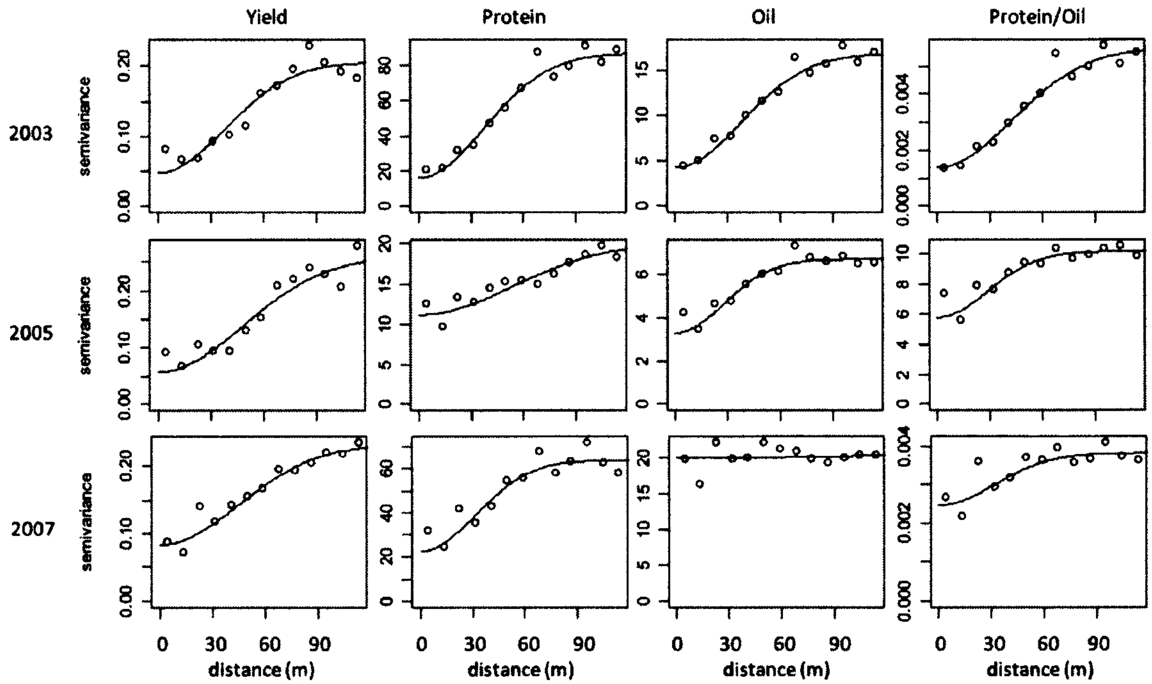

Fig. 3-3. Sample variograms and variogram models for soybean yield, protein concentration, oil concentration, and protein/oil ratio at site AN.

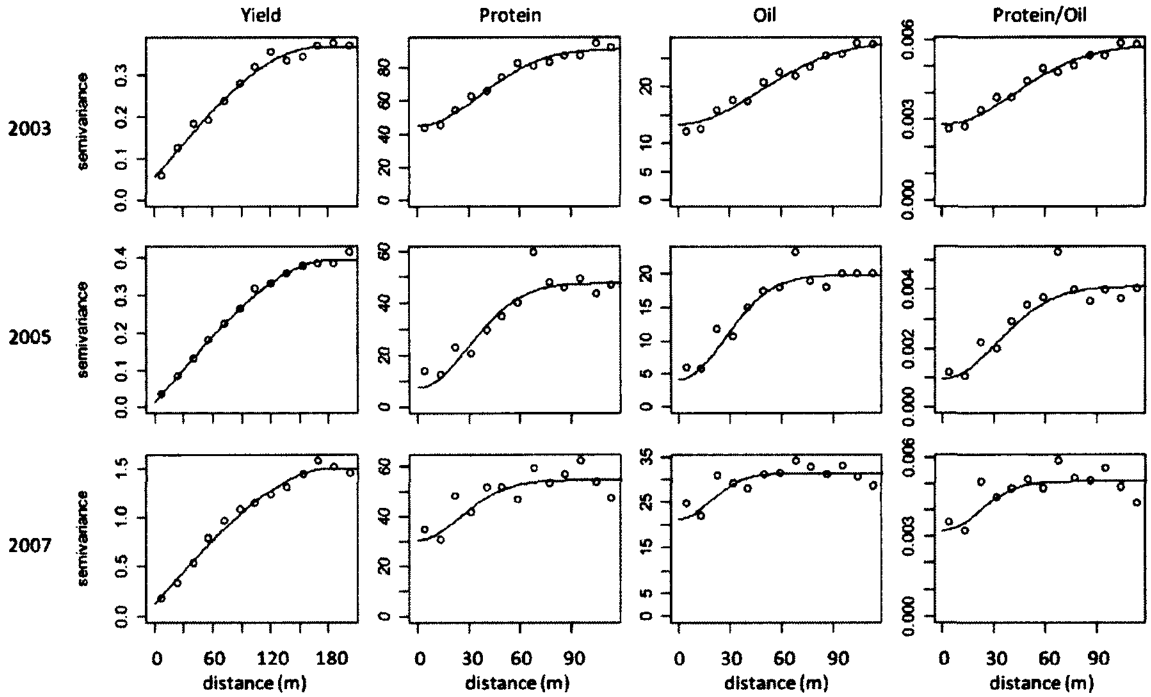

Fig. 3-4. Sample variograms and variogram models for soybean yield, protein concentration, oil concentration, and protein/oil ratio at site WB.

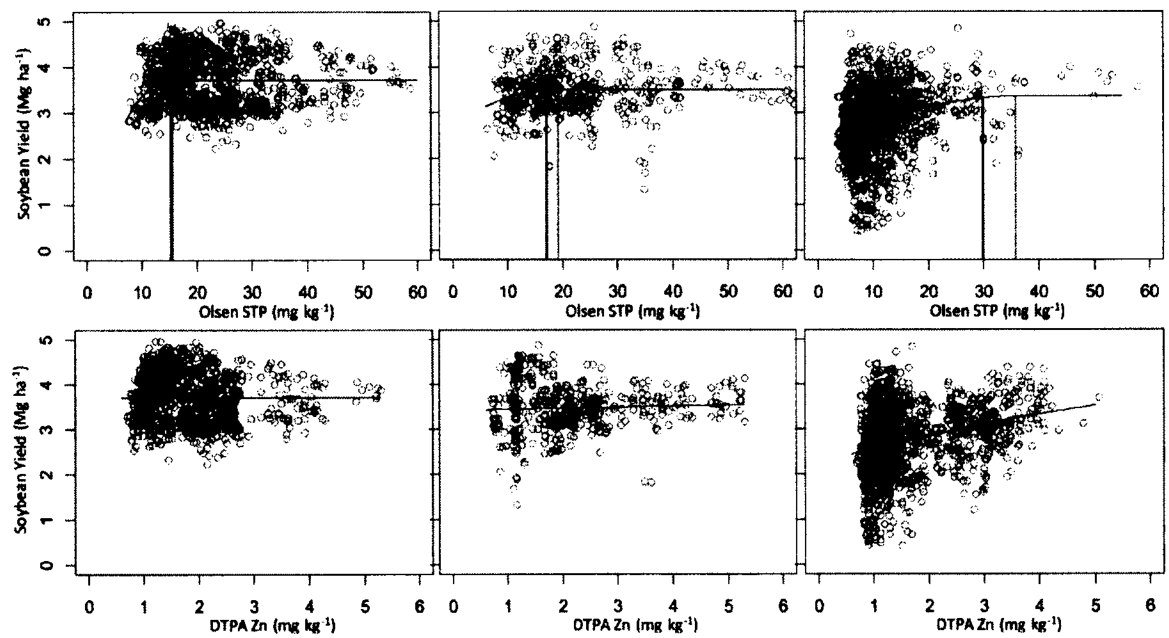

Fig. 3-5. Soybean yield plotted against Olsen soil test phosphorus (STP) (top row) and soil test Zn (bottom row) for moderately acidic soils (left column), neutral soils (center column) and moderately alkaline soils (right column). Black lines indicate the curve of best-fitting quadratic-plateau model for critical STP value. Vertical gray lines on P plots show point of yield plateau. Vertical black lines on P plots show economic optimum STP level for soybean at \$500 Mg^{-1} and P at \$1.80 kg^{-1}. Olsen STP values at economic optimum are 0 to 6 mg kg^{-1} higher than currently published recommendations in the moderately acidic and neutral soils, while the Olsen STP at economic optimum is ≈15 mg kg^{-1} higher than current recommendations in moderately alkaline soils. We observed no significant relationship ($p \leq 0.05$) between soybean yield and soil test Zn values in moderately acidic and neutral soils. In moderately alkaline soils, the quadratic plateau model indicated that higher soil test Zn levels were associated with higher soybean yields throughout the range of observations.

Table 3-1. Descriptive statistics of soybean seed yield, protein concentration, oil concentration, protein + oil concentration, and protein/oil ratio by site and year.

Year	Site	Yield				Protein				Oil				Protein+Oil				Protein/Oil			
		Mean	Min.	Max.	SD	Mean	Min.	Max.	SD	Mean	Min.	Max.	SD	Mean	Min	Max.	SD	Mean	Min.	Max.	SD
		Mg ha^{-1}				g kg^{-1}				g kg^{-1}				g kg^{-1}							
2003	AN	2.90	0.66	3.67	0.48	392	361	417	12.2	220	207	234	5.3	612	592	626	7.4	1.78	1.55	2.02	0.10
	WB	3.10	1.55	4.08	0.58	366	336	391	10.6	232	218	248	5.9	597	584	611	5.3	1.58	1.36	1.79	0.08
2005	AN	3.34	1.78	4.37	0.46	389	376	400	4.9	226	218	232	2.6	615	601	629	4.6	1.72	1.62	1.82	0.03
	WB	2.60	0.66	3.45	0.56	416	393	433	8.0	215	205	227	5.3	631	619	653	5.9	1.94	1.74	2.10	0.08
2007	AN	3.50	1.77	4.48	0.50	394	369	414	8.0	215	204	228	4.5	609	587	631	7.9	1.83	1.68	1.99	0.06
	WB	3.51	0.42	4.95	1.01	401	382	426	7.1	214	194	230	5.5	615	593	639	7.2	1.88	1.71	2.13	0.07

Table 3-2. Analysis of variance for soybean seed yield, protein concentration, oil concentration, protein + oil (P+O) concentration, and protein/oil (P/O) ratio.

Source of variation	df	Yield	Protein	Oil	Protein + Oil	Protein/Oil
		mean squares				
Year (Y)	2	551.4***	27.96***	5.37***	15.77***	0.20***
Site (S)	1	67.9*	1.26	0.01	1.02**	0.01
P rate (P)	1	60.8	0.08	0.03	0.22	0.00
N rate (N)	1	16.4	0.19	0.05	0.06	0.00
Y x S	2	377.3***	33.93***	6.15***	11.28***	0.28***
Y x P	2	2.2	0.35	0.02	0.26	0.00
S x P	1	15.7	0.70	0.30*	0.08	0.01
Y x N	2	4.0	0.03	0.01	0.01	0.00
S x N	1	10.2	0.03	0.02	0.03	0.00
P x N	1	4.0	0.01	0.01	0.04	0.00
Y x S x P	2	8.9	0.05	0.06	0.06	0.00
Y x S x N	2	6.6	0.17	0.03	0.07	0.00
Y x P x N	2	10.2	0.02	0.03	0.08	0.00
S x P x N	2	0.1	0.01	0.00	0.01	0.00
Y x S x P x N	2	0.1	0.00	0.00	0.00	0.00

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.

Table 3-3. Correlation coefficients for relationships between soybean yield, protein concentration, oil concentration, protein + oil (P+O) concentration, and protein/oil (P/O) ratio within site-years.

		2003				2005				2007			
Site	Year	Protein	Oil	P+O	P/O	Protein	Oil	P+O	P/O	Protein	Oil	P+O	P/O
AN	Yield	0.49***	-0.38***	0.53***	0.45***	NS	-0.47***	-0.37***	0.21***	-0.29***	0.12*	-0.23***	-0.25***
	Protein		-0.94***				-0.38***				-0.31***		
WB	Yield	0.41***	-0.43***	0.33***	0.43***	NS	-0.57***	-0.53***	0.35***	-0.14***	-0.06	-0.32***	-0.10**
	Protein		-0.95***				-0.67***				-0.21***		

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.

Table 3-4. Pearson correlation coefficients for the spatial patterns of soybean yield, protein concentration, oil concentration, protein + oil concentration, protein/oil ratio, protein yield, oil yield, and protein + oil yield within sites across years. Values are reported if they are significant at $p \leq 0.01$.

Site Year	— Yield —		Protein		— Oil —		Protein + Oil		Protein/Oil		—Protein Yield—		—Oil Yield—		Protein+Oil Yield	
	2005	2007	2005	2007	2005	2007	2005	2007	2005	2007	2005	2007	2005	2007	2005	2007
AN 2003	0.60	0.64	0.32	NS	0.41	NS	NS	NS	0.44	NS	0.61	0.65	0.58	0.60	0.60	0.64
2005		0.64		0.36		NS		0.26		0.64		0.63		0.63		0.64
WB 2003	0.67	0.75	0.44	NS	0.58	0.26	NS	NS	0.58	0.22	0.70	0.75	0.63	0.74	0.68	0.75
2005		0.69		0.36		0.32		0.28		0.36		0.69		0.67		0.69

Table 3-5. Parameters of best fitted variogram model for yield, protein, oil, and protein/oil ratio by site-year.

Year	Site	Yield				Protein				Oil				Protein/Oil			
		nugget	sill	nugget/sill	range m	nugget	sill	nugget/sill	range m	nugget	sill	nugget/sill	range m	nugget	sill	nugget/sill	range m
2003	AN	0.0476	0.20	0.23	94	16.1	86.7	0.19	92	4.3	16.9	0.25	93	0.0014	0.0056	0.24	106
	WB	0.0546	0.37	0.15	171	44.8	91.2	0.49	91	13.5	28.1	0.48	117	0.0028	0.0058	0.49	106
2005	AN	0.0576	0.26	0.22	119	11.2	20.1	0.56	133	3.3	6.7	0.50	69	0.0006	0.0010	0.57	71
	WB	0.00986	0.39	0.02	188	7.5	47.7	0.16	74	4.3	19.8	0.21	67	0.0010	0.0041	0.24	79
2007	AN	0.0831	0.23	0.36	111	22.5	63.8	0.35	78	20.0	20.9	0.96	266	0.0025	0.0038	0.65	79
	WB	0.1848	1.34	0.14	230	27.7	60.4	0.46	11	22.4	29.4	0.76	54	0.0032	0.0051	0.63	53

Table 3-6. Correlation coefficients between soybean yield and quality and site variables by site-year.†

Site	Year	Variable	Bray P1	Olsen P	K	pH	OM‡	TOC§	Zn	Total N	NO_3-N	NH_4-N	PBMN¶	Elevation	Slope	Curvature	Flow	Aspect
AN	2003	Yield	0.52	0.46	0.05	-0.53	-0.36	-0.21	0.28	0.08	0.10	-0.03	0.12	0.40	-0.18	0.07	0.03	-0.12
		Oil	-0.61	-0.51	0.55	0.77	0.57	0.36	0.20	0.15	0.08	0.18	-0.08	-0.67	0.24	-0.19	0.07	0.23
		Protein	0.68	0.57	-0.54	-0.82	-0.62	-0.39	-0.18	-0.13	-0.06	-0.24	0.12	0.73	-0.24	0.24	-0.08	-0.20
		Protein/Oil	0.66	0.55	-0.55	-0.81	-0.61	-0.38	-0.19	-0.14	-0.07	-0.22	0.10	0.72	-0.25	0.22	-0.08	-0.21
AN	2005	Yield	0.34	0.31	0.17	-0.23	-0.09	0.11	0.43	0.28	0.20	0.33	0.42	0.12	-0.24	-0.05	0.09	0.03
		Oil	0.03	0.06	0.22	0.20	0.04	-0.21	-0.05	-0.36	-0.28	-0.33	-0.55	-0.06	0.27	0.01	-0.13	0.21
		Protein	-0.09	-0.14	-0.67	0.01	0.00	0.13	-0.32	0.12	0.08	0.01	0.20	0.08	-0.18	0.02	0.15	-0.13
		Protein/Oil	-0.07	-0.12	-0.55	-0.11	-0.02	0.21	-0.17	0.29	0.22	0.20	0.45	0.08	-0.27	0.01	0.17	-0.20
AN	2007	Yield	0.46	0.43	-0.01	-0.43	-0.26	-0.10	0.32	-0.05	0.05	-0.39	0.09	0.28	-0.16	-0.11	0.02	0.15
		Oil	0.11	0.12	-0.02	-0.10	-0.09	-0.12	0.03	-0.14	-0.10	-0.17	-0.15	0.12	-0.03	-0.10	-0.03	0.11
		Protein	-0.42	-0.44	-0.35	0.33	0.36	0.46	-0.11	0.42	0.43	0.20	0.41	-0.35	-0.06	0.03	0.19	-0.15
		Protein/Oil	-0.32	-0.34	-0.20	0.26	0.27	0.35	-0.09	0.34	0.32	0.22	0.35	-0.28	-0.02	0.08	0.14	-0.16
WB	2003	Yield	0.43	0.37	-0.27	-0.68	-0.52	-0.22	0.14	-0.07	-0.14	0.06	0.57	0.43	0.48	-0.02	-0.18	0.18
		Oil	-0.47	-0.48	0.34	0.59	0.34	0.02	-0.15	0.32	0.31	0.22	-0.50	-0.53	-0.23	-0.17	0.11	-0.09
		Protein	0.52	0.51	-0.28	-0.56	-0.37	-0.09	0.23	-0.21	-0.21	-0.17	0.48	0.51	0.24	0.14	-0.05	0.11
		Protein/Oil	0.50	0.50	-0.32	-0.59	-0.36	-0.05	0.19	-0.27	-0.26	-0.19	0.50	0.52	0.24	0.16	-0.08	0.10
WB	2005	Yield	0.59	0.49	0.01	-0.61	-0.66	-0.26	0.32	-0.14	-0.14	0.03	0.51	0.41	0.46	0.12	0.04	0.30
		Oil	-0.46	-0.63	0.24	0.72	0.44	0.06	-0.11	-0.25	-0.23	0.02	-0.53	-0.58	-0.41	-0.12	0.10	-0.19
		Protein	0.02	0.32	-0.32	-0.42	-0.01	0.20	-0.06	0.43	0.40	-0.10	0.26	0.40	0.09	0.07	-0.15	0.02
		Protein/Oil	0.29	0.54	-0.30	-0.65	-0.28	0.06	0.05	0.36	0.33	-0.06	0.45	0.55	0.30	0.10	-0.14	0.13
WB	2007	Yield	0.60	0.48	-0.12	-0.67	-0.61	-0.37	0.40	0.32	-0.03	0.32	0.57	0.49	0.59	-0.02	-0.18	0.17
		Oil	-0.10	-0.15	0.19	0.20	0.05	-0.06	-0.11	-0.05	0.06	-0.11	-0.17	-0.13	-0.07	-0.01	0.07	-0.06
		Protein	-0.08	-0.04	-0.01	0.05	0.10	0.09	-0.01	0.02	0.02	0.00	-0.06	-0.06	-0.15	0.00	0.04	0.03
		Protein/Oil	-0.02	0.04	-0.10	-0.06	0.05	0.11	0.05	0.04	-0.02	0.06	0.04	0.02	-0.08	0.00	-0.01	0.05

†Correlations differ from zero ($p \leq 0.01$) if $\rho > 0.14$ for site AN in all years and for site WB in years 2003 and 2005; for site WB in 2007, correlations differ from zero ($p \leq 0.01$) if $\rho > 0.10$.

‡Organic Matter.

§ Total Organic C.

¶ Phosphate-borate mineralizable N.

Table 3-7. Rotated factor loadings for soil variables and other factor analysis information by site-year.

					Factors			
			1	2	3	4	5	
Site	Year	Variable	"P Availability"	"Mineralization and pH"	"N Availability"	"K and Zn"	"Residual NH_4–N"	Uniquenesses
					Factor Loadings			
WB	2003	Bray P1	0.92	0.34	0.01	0.32	-0.08	0.01
		Olsen P	0.89	0.31	-0.05	0.26	-0.15	0.06
		K	0.16	-0.14	0.29	0.66	-0.03	0.33
		pH	-0.23	-0.69	0.19	-0.09	-0.15	0.20
		OM†	-0.50	-0.33	-0.21	0.20	-0.15	0.21
		TOC‡	-0.58	0.20	0.07	-0.07	-0.01	0.78
		Zn	0.40	0.21	-0.05	0.85	0.10	0.49
		PBMN§	-0.01	1.07	0.06	0.10	-0.04	0.01
		NO_3–N	0.04	0.02	1.00	0.04	-0.11	0.02
		NH_4–N	-0.41	-0.01	0.08	0.24	0.88	0.01
		Total N	-0.08	0.00	0.88	0.10	0.21	0.01
		Elevation	0.38	0.54	-0.11	-0.20	-0.07	0.06
		Slope	0.09	0.41	0.26	-0.45	-0.04	0.43
		Curvature	0.38	-0.13	0.06	-0.40	-0.20	0.65
		Flow	0.16	-0.13	0.14	0.36	0.06	0.80
		Aspect	0.10	-0.10	-0.10	-0.15	0.45	0.77
		Eigenvalue	3.0	2.5	2.1	2.0	1.2	
		% of variance	19	16	13	13	7	
			"Mineralization and pH"	"P Availability"	"N Availability"	"K and Zn"	"Residual NH_4–N"	Uniquenesses
WB	2005	Bray P1	-0.08	1.07	-0.04	0.23	0.02	0.01
		Olsen P	0.02	0.92	0.18	-0.06	0.10	0.13
		K	-0.25	0.21	0.02	0.79	0.02	0.27
		pH	-0.90	-0.04	-0.15	0.00	0.00	0.11
		OM	-0.67	-0.26	0.16	-0.01	0.02	0.24
		TOC	-0.05	-0.28	0.18	-0.06	0.08	0.86
		Zn	0.40	0.01	-0.06	0.84	-0.12	0.43
		PBMN	1.05	-0.17	-0.05	0.03	0.13	0.13
		NO_3–N	-0.02	0.05	0.90	-0.01	-0.25	0.01
		NH_4–N	0.09	0.08	-0.01	-0.04	1.01	0.01
		Total N	0.08	0.03	1.02	0.00	0.17	0.01
		Elevation	0.73	0.13	0.10	-0.20	-0.13	0.09
		Slope	0.44	0.13	-0.19	-0.37	0.03	0.40
		Curvature	0.04	0.20	-0.06	-0.32	-0.13	0.75
		Flow	-0.09	0.07	-0.06	0.37	0.05	0.82
		Aspect	0.38	-0.09	0.18	0.14	0.05	0.87
		Eigenvalue	3.5	2.3	2.1	1.8	1.2	
		% of variance	22	14	13	11	8	
			"P Availability"	"Residual NH_4–N"	"N Availability"	"OM"	"K"	Uniquenesses
WB	2007	Bray P1	1.12	-0.11	-0.03	0.19	0.05	0.01
		Olsen P	1.10	-0.06	0.02	0.48	0.24	0.01
		K	0.04	-0.21	-0.01	0.07	-0.66	0.50
		pH	-0.58	-0.06	-0.12	0.27	-0.11	0.23
		OM	-0.55	0.07	0.05	0.54	-0.11	0.05
		TOC	-0.48	-0.12	0.26	0.18	0.19	0.62
		Zn	0.17	0.74	0.04	0.14	-0.12	0.38
		PBMN	0.25	0.31	0.29	-0.32	0.13	0.26
		NO_3–N	0.16	-0.86	0.60	-0.06	-0.12	0.03
		NH_4–N	-0.11	1.00	0.34	0.15	0.08	0.01
		Total N	-0.02	0.13	0.96	-0.04	-0.04	0.01
		Elevation	0.53	0.03	0.01	-0.26	0.42	0.06
		Slope	0.57	-0.02	0.04	-0.32	0.00	0.36
		Curvature	0.16	-0.15	-0.22	-0.07	0.53	0.57
		Flow	-0.10	-0.06	-0.06	-0.02	-0.30	0.87
		Aspect	-0.11	-0.29	0.04	-0.65	0.12	0.57
		Eigenvalue	4.1	2.6	1.6	1.4	1.2	
		% of variance	26	16	10	9	7	
			"N Availability"	"P Availability"	"Residual NH_4–N"	"Landscape"	"K and Zn"	Uniquenesses
AN	2003	Bray P1	0.01	1.05	0.07	0.04	-0.04	0.01
		Olsen P	0.07	1.11	0.26	0.04	0.01	0.09
		K	-0.22	-0.15	0.11	0.04	0.96	0.04

Table 3-7 continued…

		pH	0.20	-0.44	0.19	0.37	0.07	0.11
		OM	0.47	-0.24	0.41	0.04	0.05	0.11
		TOC	0.88	-0.25	-0.01	0.02	-0.06	0.04
		Zn	0.46	0.20	-0.11	-0.08	0.69	0.27
		PBMN	0.83	0.05	-0.06	-0.16	-0.17	0.43
		NO_3-N	1.16	0.05	-0.41	0.01	0.02	0.01
		NH_4-N	-0.50	0.11	0.98	-0.20	0.04	0.41
		Total N	1.10	0.05	-0.21	-0.04	0.02	0.01
		Elevation	-0.25	0.40	-0.24	-0.36	0.00	0.11
		Slope	-0.32	-0.09	-0.47	0.79	-0.02	0.29
		Curvature	-0.07	-0.27	-0.16	-0.49	0.06	0.77
		Flow	0.44	-0.01	0.09	-0.06	-0.07	0.77
		Aspect	0.02	0.06	-0.43	0.68	0.04	0.57
		Eigenvalue	5.2	3.0	2.0	1.7	1.5	
		% of variance	32	19	12	11	9	
			"N Availability"	"P Availability"	"Residual NH_4–N"	"Landscape"	"K and Zn"	Unique-nesses
AN	2005	Bray P1	-0.01	0.92	0.01	0.03	0.03	0.27
		Olsen P	-0.02	0.91	-0.01	-0.01	0.09	0.24
		K	-0.23	-0.04	-0.09	0.04	0.79	0.51
		pH	0.40	-0.03	-0.54	0.25	0.05	0.37
		OM	0.43	-0.06	-0.61	-0.25	0.10	0.24
		TOC	0.88	-0.01	-0.20	-0.01	-0.03	1.00
		Zn	0.27	0.24	0.06	-0.05	0.65	0.55
		PBMN	0.97	-0.04	0.53	0.07	-0.11	0.34
		NO_3-N	0.93	-0.03	-0.08	0.02	0.00	0.33
		NH_4-N	0.16	-0.19	0.49	-0.43	0.31	0.57
		Total N	0.98	0.03	0.07	-0.05	0.00	0.08
		Elevation	-0.36	0.32	0.45	-0.10	-0.12	0.31
		Slope	-0.14	-0.18	0.17	0.77	0.07	0.52
		Curvature	-0.07	0.06	0.13	-0.24	-0.19	0.77
		Flow	0.55	0.09	-0.05	-0.03	-0.10	0.71
		Aspect	0.10	0.15	-0.01	0.71	0.07	0.60
		Eigenvalue	4.5	1.9	1.5	1.5	1.2	
		% of variance	28	12	9	9	8	
			"N Availability"	"pH"	"P Availability"	"K and Zn"	"Residual NH_4-N"	Unique-nesses
AN	2007	Bray P1	-0.07	-0.18	0.87	-0.01	-0.06	0.01
		Olsen P	-0.15	0.08	1.00	-0.03	0.01	0.06
		K	-0.26	0.01	-0.07	1.02	0.14	0.01
		pH	-0.08	0.95	-0.09	-0.08	-0.03	0.13
		OM	0.17	0.86	0.12	-0.01	0.14	0.13
		TOC	0.73	0.41	-0.02	-0.09	-0.03	0.02
		Zn	0.49	-0.14	0.21	0.62	-0.12	0.34
		PBMN	0.98	-0.25	-0.07	-0.15	0.04	0.19
		NO_3-N	1.03	-0.01	-0.07	-0.04	-0.10	0.01
		NH_4-N	0.03	0.30	-0.13	0.25	0.80	0.08
		Total N	0.86	0.10	-0.08	0.02	0.14	0.01
		Elevation	-0.11	-0.75	0.18	-0.09	0.07	0.12
		Slope	-0.18	-0.03	-0.25	0.13	-0.51	0.59
		Curvature	-0.05	-0.31	-0.09	-0.05	0.33	0.81
		Flow	0.31	0.21	0.08	-0.08	0.11	0.77
		Aspect	0.04	0.16	0.01	0.03	-0.65	0.57
		Eigenvalue	3.8	2.8	2.0	1.6	1.5	
		% of variance	24	17	12	10	10	

† Organic Matter.
‡ Total Organic C.
§ Phosphate-borate mineralizable N.

Table 3-8. Significant ($p \leq 0.01$) canonical correlations between soybean yield, protein, and oil concentrations and soil chemical and topographical variables for pooled sites and years.

Canonical Variables	Soy 1 vs. Soil 1	Soy 2 vs. Soil 2	Soy 3 vs. Soil 3
Canonical correlation coefficient	0.72	0.48	0.43
Soybean Variables	p1	p2	p3
Yield	-0.82	0.56	0.09
Protein	-0.44	-0.67	-0.60
Oil	0.70	0.71	-0.02
Site Variables	q1	q2	q3
Bray P	-0.55	0.47	-0.05
Olsen P	-0.49	0.33	0.13
K	0.11	0.32	0.46
pH	0.83	-0.23	-0.14
OM†	0.49	-0.23	0.03
TOC‡	0.11	0.22	0.09
Zn	-0.10	0.43	0.13
PBMN§	-0.35	0.43	-0.34
NO_3-N	0.12	0.09	-0.30
NH_4-N	0.43	0.57	-0.11
Total N	0.23	0.24	-0.32
Elevation	-0.58	0.19	0.06
Slope	-0.37	0.36	0.21
Curvature	-0.04	-0.13	0.02
Flow	0.11	0.01	-0.08
Aspect	-0.12	0.20	0.02

† Organic Matter.
‡ Total Organic C.
§ Phosphate-borate mineralizable N.

Table 3-9. Significant ($p \leq 0.01$) canonical correlations between soybean yield, protein, and oil concentrations and soil chemical and topographical variables by site-year.

Site	Year	Canonical Variables	Soy 1 vs. Site 1	Soy 2 vs. Site 2	Soy 3 vs. Site 3
AN	2003	canonical correlation coefficient	0.91	0.66	0.34
		soybean variables	p1	p2	p3
		Yield	-0.64	0.77	-0.01
		Protein	-0.98	-0.19	0.02
		Oil	0.90	0.25	-0.35
		site variables	q1	q2	q3
		Bray P1	-0.78	0.12	-0.11
		Olsen P	-0.66	0.15	-0.11
		K	0.50	0.68	-0.15
		pH	0.91	0.01	-0.11
		OM†	0.69	0.08	0.10
		TOC‡	0.42	0.08	-0.05
		Zn	0.11	0.68	0.02
		PBMN§	-0.14	0.07	-0.23
		NO_3-N	0.03	0.22	-0.15
		NH_4-N	0.24	0.22	0.43
		Total N	0.11	0.27	-0.13
		Elevation	-0.80	-0.14	-0.04
		Slope	0.28	-0.04	-0.22
		Curvature	-0.25	-0.16	-0.38
		Flow	0.07	0.14	0.13
		Aspect	0.22	0.01	-0.46
AN	2005	canonical correlation coefficient	0.77	0.70	0.45
		soybean variables	p1	p2	p3
		Yield	-0.89	0.38	0.27
		Protein	0.48	0.88	0.01
		Oil	0.43	-0.67	0.61
		site variables	q1	q2	q3
		Bray P1	-0.36	0.07	0.66
		Olsen P	-0.36	-0.02	0.60
		K	-0.53	-0.78	0.09
		pH	0.29	-0.16	0.12
		OM	0.10	-0.06	-0.09
		TOC	-0.09	0.27	-0.19
		Zn	-0.64	-0.15	0.31
		PBMN	-0.45	0.60	-0.42
		NO_3-N	-0.23	0.28	-0.26
		NH_4-N	-0.42	0.27	-0.24
		Total N	-0.32	0.38	-0.29
		Elevation	-0.08	0.17	0.16
		Slope	0.20	-0.41	0.03
		Curvature	0.06	-0.01	-0.06
		Flow	-0.03	0.27	0.03
		Aspect	-0.04	-0.20	0.46
AN	2007	canonical correlation coefficient	0.08	0.66	
		soybean variables	p1	p2	
		Yield	-0.99	0.09	
		Protein	0.38	0.92	
		Oil	-0.21	-0.12	
		site variables	q1	q2	
		Bray P1	-0.64	-0.38	
		Olsen P	-0.60	-0.44	
		K	-0.03	-0.59	
		pH	0.59	0.26	
		OM	0.37	0.41	
		TOC	0.18	0.66	
		Zn	-0.43	0.01	
		PBMN	-0.06	0.68	
		NO_3-N	-0.01	0.70	
		NH_4-N	0.54	0.05	
		Total N	0.12	0.62	

Table 3-9 continued…

		Elevation	-0.40	-0.37	
		Slope	0.20	-0.20	
		Curvature	0.15	-0.04	
		Flow	-0.01	0.32	
		Aspect	-0.21	-0.13	
WB	2003	canonical correlation coefficient	0.79	0.58	0.48
		soybean variables	p1	p2	p3
		Yield	-0.95	0.21	-0.24
		Protein	-0.67	-0.29	0.68
		Oil	0.69	0.54	-0.47
		site variables	q1	q2	q3
		Bray P1	-0.65	0.04	0.56
		Olsen P	-0.59	-0.06	0.58
		K	0.42	0.35	0.00
		pH	0.95	0.16	-0.11
		OM	0.68	-0.23	-0.16
		TOC	0.24	-0.44	-0.11
		Zn	-0.22	0.26	0.49
		PBMN	-0.80	-0.10	0.13
		NO_3-N	0.27	0.58	0.10
		NH_4-N	0.03	0.48	-0.21
		Total N	0.21	0.67	0.04
		Elevation	-0.67	-0.29	0.32
		Slope	-0.59	0.22	-0.11
		Curvature	-0.05	-0.31	0.18
		Flow	0.22	0.18	0.30
		Aspect	-0.23	0.13	0.02
WB	2005	canonical correlation coefficient	0.85	0.75	0.29
		soybean variables	p1	p2	p3
		Yield	-0.97	0.15	-0.17
		Protein	-0.10	-0.97	-0.22
		Oil	0.73	0.66	-0.20
		site variables	q1	q2	q3
		Bray P1	-0.73	0.03	0.40
		Olsen P	-0.67	-0.39	0.41
		K	0.04	0.43	0.05
		pH	0.80	0.47	0.11
		OM	0.79	-0.08	0.03
		TOC	0.29	-0.29	-0.32
		Zn	-0.34	0.15	-0.36
		PBMN	-0.64	-0.27	-0.05
		NO_3-N	0.08	-0.56	0.05
		NH_4-N	-0.03	0.12	0.27
		Total N	0.09	-0.61	0.10
		Elevation	-0.56	-0.47	-0.02
		Slope	-0.58	-0.08	0.21
		Curvature	-0.14	-0.07	-0.12
		Flow	-0.01	0.22	-0.08
		Aspect	-0.35	0.03	-0.22
WB	2007	canonical correlation coefficient	0.86	0.54	0.42
		soybean variables	p1	p2	p3
		Yield	-1.00	-0.03	-0.02
		Protein	0.16	0.95	-0.27
		Oil	0.24	-0.63	-0.74
		site variables	q1	q2	q3
		Bray P1	-0.64	-0.27	0.35
		Olsen P	-0.57	-0.05	0.43
		K	0.01	-0.25	-0.64
		pH	0.77	0.09	-0.42
		OM	0.60	0.45	-0.32
		TOC	0.46	0.21	0.14
		Zn	-0.64	0.32	-0.15
		PBMN	-0.63	0.07	0.06
		NO_3-N	0.16	-0.34	0.28
		NH_4-N	-0.55	0.47	-0.33

Table 3-9 continued...

Total N	-0.39	0.09	0.01
Elevation	-0.47	-0.22	0.41
Slope	-0.58	-0.29	0.42
Curvature	0.10	-0.19	0.40
Flow	0.14	-0.14	-0.13
Aspect	-0.15	-0.27	0.42

† Organic Matter.
‡ Total Organic C.
§ Phosphate-borate mineralizable N.

CHAPTER 4: Site-Specific Corn and Soybean Yield and Quality Response to N-P-S-Zn Starter Fertilizer[1]

ABSTRACT

Starter fertilizers are commonly used in row-crop production in the North-Central United States. This experiment was conducted to determine response of corn [*Zea mays* L.] and soybean [*Glycine max* (L.) Merr.] grain yield and quality to an N-P-S-Zn starter fertilizer across a range of N and P fertility levels and to relate starter response to site-specific soil parameters. Overall, starter application to corn increased yield by 543 kg ha^{-1} (+5.2%). Yield response was positively related to N and P fertility, and yield response increased to 1371 kg ha^{-1} (+12%) within treatments receiving the highest rates of fertilizer N and P. Yield response was positively related to soil N and negatively related to soil test Zn. Starter application resulted in 1.87 g kg^{-1} increase in corn protein (+2.3%), a 0.63 g kg^{-1} increase in oil concentration (+1.6%) and a 2.63 g kg^{-1} decrease in starch concentration (-0.2%). Corn quality responses were also greater at higher levels of N and P availability. Overall, starter application to soybean did not significantly affect yield, although positive responses were noted at low levels of soil test P (STP), total soil organic C, and soil organic matter. Starter fertilizer increased soybean protein concentration by 1.76 g kg^{-1} (+0.4%) and decreased soybean oil concentration by 2.36 g kg^{-1} (-1.1%). In this experiment, corn response to starter fertilizer appeared most associated with the S and Zn components of the starter and exhibited synergistic interaction with N and P availability. Starter applications to soybeans would be beneficial only if applied site-specifically to low P (<12 ppm Olsen STP) and low organic matter (< 5%) soils.

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[1] P. Anthony, G. Malzer, M. Zhang, and S. Sparrow. Prepared for publication in Agronomy Journal.

Abbreviations: AIC, Akaike Information Criterion; DEM, digital elevation model; OM, organic matter; PBMN, phosphate borate mineralizable N; STP, soil test phosphorus

INTRODUCTION

Application of starter fertilizer for corn production is a common practice in the north-central Corn Belt of the United States. Agronomic benefits attributed to starter fertilizer application include increased early growth (Mallarino et al., 2011; Randall and Hoeft, 1988; Rehm and Lamb, 2009), higher efficiency in fertilizer utilization by the crop (Randall and Hoeft, 1988), lower grain moisture at harvest (Bundy et al., 2005), and increased yields (Bundy et al., 2005; Randall and Hoeft, 1988) especially in seasons when the growth period is limited (Bullock et al., 1993; Bundy and Andraski, 1999). Corn response to starter fertilizer has been related to both N and P components (Randall and Hoeft, 1988). Responses to starter fertilizer application of P have been noted to be higher in soils with low STP values (Vetch and Randall, 2002; Rehm et al., 1988; Bermudez and Mallarino, 2002) and in cool and wet environmental conditions that inhibit root growth and P uptake (Rehm et al., 1988; Sawyer et al., 2008). When soil STP levels are high, starter responses have been related to the N content of the starter (Rehm and Lamb, 2009; Vetch and Randall, 2002). Studies of starter fertilizer applications to soybeans have not demonstrated yield increases (Buah et al., 2000; Rehm et al., 1988), and starter applications to soybean are often avoided due to concern about the sensitivity of soybean seedlings to fertilizer salt injury (Rehm et al., 2001). Recent research indicating corn yield responses to S and Zn fertilization (Randall and Vetch, 2006; Vetch et al., 2009) has led to interest among farmers in including these nutrients in starter fertilizer applications for corn. Research summaries have also reported responses of soybean yield and quality to S applications (Bly et al., 2001), and starter fertilizer applications could be an efficient way to increase soybean yield and quality.

While benefits to starter fertilizer have been demonstrated across many environments, use of starter leads to higher production costs per unit area. Planters must be outfitted with specialized application equipment, and supplying fertilizer to the planter increases logistical challenges during the time-sensitive spring planting season. Nutrients in starter fertilizer mixtures tend to have a higher price per unit of elemental nutrient. In addition, some research has indicated that starter fertilizer application may not increase yields compared with similar rates of spring-applied broadcast fertilizer (Kaiser et al., 2005).

While corn yield responses to N-P starters across levels of P fertility have been well-explored, we are not aware of studies that observed response to starter across levels of N fertility. Synergistic interaction effects are often observed in plant nutrition, and responses to starters containing S and Zn could be greater when N and P are both highly available. Literature on field-scale variability in response to starter fertilizer is also very limited. As site-specific fertilizer rate control equipment has become widely available, site-specific starter applications could be an efficient way to optimize nutrient use. This experiment was conducted to determine response of corn and soybean grain yield and quality to an N-P-S-Zn starter fertilizer across a range of N and P fertility levels and to relate starter response to site-specific soil parameters.

MATERIALS AND METHODS

Site Description

Trials were conducted in 2006 and 2007 on a 16-ha field in Brown County, south-central Minnesota (44°08'N, 94°41'W). The site was initially developed for agriculture in the 1860s, and has been in a corn–soybean rotation since the 1960s. The site had received no manure application within the 10 yr prior to the initiation of the research. The soils at the site lie within a Nicollet–Clarion–Webster association, and consist of the Canisteo series (fine-loamy, mixed, superactive, calcerous, mesic Typic Endoaquolls), Clarion series (fine-loamy, mixed, superactive, mesic Typic Hapludolls), Nicollet series (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Okoboji series (fine, smectitic, mesic Cumulic Vertic Endoaquolls), and the Fieldon-Canisteo complex (fine-loamy to coarse-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) (Christensen, 1988; USDA-NRCS, 2011). Soils formed from calcareous glacial till. The site has limited tile drainage. Field management is typical for a corn–soybean rotation in south-central Minnesota. Tillage practices consisted of single-pass fall chisel tillage of soybean stubble and single-pass spring field cultivation prior to corn planting, and a single-pass fall disk-chisel tillage of corn stubble and a single-pass spring field cultivation prior to soybean planting.

Experimental Design

The fertility experiment included three replications of 18 treatments in a split-split-plot arrangement of a randomized complete-block design. Phosphorus (0 and 56 kg P ha^{-1}) was the main plot; N treatments (0, 51, 101, 152, and 202 kg N ha^{-1}) were applied in strips across the field, and placement of these strips was randomized within the P treatments. Each of the N strips was split into two treatments. One treatment received no starter fertilizer; the other treatment received 135 kg ha^{-1} of a dry fertilizer mixture produced by The Mosaic Company (Plymouth, MN, USA), consisting of 120 g kg^{-1} N, 210 g kg^{-1} P, 100 g kg^{-1} S, and 10 g kg^{-1} Zn. Starter was applied in a band placement 5 cm beside and 5 cm below the seed. Nutrient application rates of the starter fertilizer were 16 kg ha^{-1} N, 28 kg ha^{-1} P, 14 kg ha^{-1} S, and 1.35 kg ha^{-1} Zn. K was applied to the entire field at a rate of 93 kg K ha^{-1}. Three extra 101 kg N ha^{-1} nitrogen strips were included to avoid having 0 kg N ha^{-1} treatments repeated on the same strip in consecutive rotations; instead, the 0 N treatments were applied to a strip that had received a 101 kg N ha^{-1} rate in the previous N application. All other treatments were applied to the same strip in each year of application. The starter fertilizer treatments were applied at planting in both the corn (2006) and soybean (2007) years. The N, P, and K treatments were applied prior to the corn year of the corn-soybean rotation. N was applied as anhydrous ammonia (82–0–0) with the nitrification inhibitor nitrapyrin (Dow AgroSciences, Indianapolis, IN, USA), P was broadcast applied as diammonium phosphate (18–46–0), and K was broadcast applied as muriate of potash (KCl, 0–0–60) in November 2005. In 2006, the corn hybrid Dekalb 51-39 planted was planted on 24 April at 79,000 seeds ha^{-1}; in 2007, the soybean cultivar Midwest 2031 was planted on 15 May at 370,000 seeds ha^{-1}.

Yield Measurements

In the falls of 2006 and 2007, plots were harvested with a modified Model 8 Massey Ferguson plot combine (AGCO Corp., Duluth, GA, USA). This combine was equipped with an electronic ground distance monitor and a computerized HarvestMaster weigh cell (HarvestMaster, Logan, UT, USA). Yield is reported as kg ha^{-1} on a 15.5 % moisture basis for corn and a 13% moisture basis for soybeans. Yield measurements were taken from 15 m sections along selected 4.5-m wide transects in each field. These 15-m sections corresponded to the 0.014-ha soil sampling grid cells. One-half of each soil sampling grid cell received the starter treatment; one-half received no starter. In 2006, 1242 harvest observations were made, representing all corn treatments (18 treatments of 23 observations in 3 blocks). In 2007, 833 harvest observations were collected. Saturated fall soil conditions restricted harvesting to the western 2/3 of the field. Within this portion of the field, observations representing all treatment combinations were made. Grain samples were retained from each yield measurement and were analyzed for quality components using near infrared spectroscopy (NIRS), using a Foss full scanning 6500 monochrometer fitted with NIRS equations developed by the University of Minnesota using ISIscan software (Infrasoft Intl., State College, PA, USA) and validated by Caltest (Clifton Park, NY, USA). Corn samples were analyzed for protein, oil, and starch; soybean samples were analyzed for protein and oil. Concentrations are reported as g kg^{-1} on a dry weight (0% moisture) basis.

Soil Chemical and Topographical Variables

The soil sampling and analysis protocol is described in detail by Anthony et al. (2012). Briefly, soils were sampled in the fall of each year. Samples were taken from 9- by 15-m (0.014 ha) grid cells along a subset of the 36 transects of the N plots. At the initiation of the N and P experiment in the fall of 2001, 0- to 15-cm samples from each cell were analyzed for Bray P, Olsen P, K, pH, organic matter (OM), and Zn; 0- to 60-cm samples from each cell were analyzed for total organic C, total Kjeldahl N, NH_4–N, NO_3–N, and mineralizable N. To determine mineralizable N, we used the phosphate borate mineralizable N (PBMN) test described by Gianello and Bremner (1988) as modified by Clay and Malzer (1993). In all falls following, 0- to 15-cm samples were analyzed for Bray P, Olsen P, K, and pH. In odd-numbered falls following, which were subsequent to the soybean harvest and preceding the corn year in the rotation, 0- to 60-cm samples were taken and analyzed for NH_4–N, NO_3–N, and mineralizable N. Soil test values for grid cells which were not sampled in a particular year were estimated using cokriging in the Spatial Analyst extension of Arc View 9.3 (Environmental Systems Research Inst., Redlands, CA, USA). Soil test values for each 0.014-ha grid cell were extracted as the cell mean from kriged rasters and used for further analysis.

Elevation and position measurements were made on each field using survey grid GPS (horizontal accuracy +/- 0.5 m) and land-based laser (vertical accuracy +/- 0.05 m). Elevation measurements were made on a semi-regular grid with mean distance between points of approximately 20 m. These coordinates were used to create a digital elevation model (DEM) of the fields using kriging in the Spatial Analyst extension of ArcView 9.3. The DEM raster was used to generate slope, curvature, and aspect rasters using these respective tools in the ArcView Spatial Analyst. The Fill, Flow Direction, and Flow Accumulation tools of the Arc View 9.3 Spatial Analyst extension were used to derive a hydrologic flow accumulation raster for each field. Mean values of the elevation, slope, curvature, aspect, and flow accumulation for each 0.014-ha grid cell of the field were extracted and used in further analysis.

Statistical Analysis

Response to starter fertilizer was calculated as the difference between the observed yield or quality response variable with starter fertilizer and without starter fertilizer within each 0.014-ha grid cell. Descriptive statistics were calculated for each yield and quality variable. Overall significance of starter was determined using parametric (Welch's t-test) or nonparametric (Kolomogorov-Smirnov test) approaches, depending on the distribution of data. Welch's t-test was used to test significance for normally-distributed data due to unequal variances of sample means. Significance of fertilizer treatments was determined using analysis of variance. Pearson's correlation coefficients were calculated between each soil variable and yield and quality components. Significance of soil variables was determined using backwards stepwise regression based on Aikaike's information criterion (AIC). Statistical analyses were conducted using R 2.12.1 (R Development Core Team, 2010)

We used geostatistics to analyze the spatial structure of variability in response of yield and quality to starter fertilizer. When necessary, data was log-transformed in order to normalize the distributions and most closely meet the assumption of intrinsic stationarity. Sample variograms were calculated and were fitted with exponential, spherical or gaussian models using weighted least-squares regression; models were selected to minimize the Akaike information criterion (AIC). Values were estimated for the variogram range, sill, and nugget. The proportion of variance in the data attributable to spatial correlation was characterized by the nugget/sill ratio. Geostatistical analysis was conducted using the geoR package (Ribeiro and Diggle, 2001) for R version 2.12.1 (R Development Core Team, 2010).

RESULTS AND DISCUSSION

Corn Yield and Quality

Across all N and P treatments and soil variability, starter fertilizer application had a significant effect on corn yield, increasing production, on average, by 543 kg ha^{-1} (5.2% increase). Yield response to starter was negatively correlated with absolute yield levels, although the strength of this correlation was weak (Fig. 4-1). The magnitude of corn yield response to starter differed across N and P treatments and was related to soil variables. Corn yield response to the starter fertilizer treatment differed significantly by N rate and by N rate by P rate interaction (Fig. 4-2). Yield response to starter rose to 1371 kg ha^{-1} (12% increase) at the combination of highest N and P rates. We cannot explain the large differences in effect of P at the 101 kg ha^{-1} N rate (Fig. 4-2). Variogram analysis indicated that yield response to starter exhibited spatial correlation at all levels of fertilizer N and P (variograms not shown). Spatial variation in yield response was significantly related to Olsen STP, soil pH, Zn, and mineralizable N (Table 4-1). Response to starter was greater at higher Olsen STP values, higher soil pH values, higher levels of mineralizable N, and lower levels of Zn. When we looked only at relations of response to soil variables at the highest level of fertilizer N, we found that that response to starter was significantly related to fertilizer P rate, mineralizable N, and NO_3–N, and soil Zn (Table 4-2). Response was greater where fertilizer P was applied. Response increased with increasing levels of soil mineralizable N and NO_3–N, and response declined with increasing levels of soil Zn.

We interpret these results as being consistent with von Liebig's "Law of the Minimum," which states that yield is limited by the most limiting nutrient. If the N or P components of the starter were those with the greatest impact, we would expect response to be greatest at the lowest levels of N or P fertility. Such responses to starter fertilizers containing only N and P have been previously observed by Bermudez and Mallarino (2002) and Vetch and Randall (2002). In this experiment, however, yield response to starter increased with increasing levels of N and P fertility. We interpret this synergistic response to indicate that corn yield response to starter was most related to the S and Zn components of the fertilizer. When these nutrients were supplied through the starter, the crop was able to utilize higher levels of P and N, whether supplied through fertilizer, through available nutrients already in the soil, or through soil mineralization. Nitrogen-sulfur interaction effects on corn yield have been previously reported (Rabuffetti and Kamprath, 1977), but have not been consistent (Rehm and Clapp, 2008). While the crop yield response to S that we observed is inferred from the nature of the interaction effect, the response to Zn may be observed more directly, as response was greatest when soil test Zn was lowest.

Across all N and P treatments and soil variability, starter fertilizer resulted in significantly lower starch content and higher protein and oil content. Although significant, mean responses were small. On average, starter fertilizer reduced starch content by 2.63 g kg^{-1} (0.2% decrease), raised protein by 1.87 g kg^{-1} (2.3% increase), and raised oil content by 0.63 g kg^{-1} (1.6% increase). Corn quality responses were negatively correlated with absolute values of corn quality (Fig. 4-1), and this correlation was particularly strong for oil and starch content. Responses differed by N rate and N rate by P rate interaction (Fig. 4-2). For oil and protein, the N rate by P rate interaction effect was due to a large and unexplained difference in response across P rates at the 101 kg ha^{-1} N rate (Fig. 4-2). Corn quality responses also related to soil variables. After accounting for fertilizer N and P effects, response of oil concentration was positively related to Olsen STP and negatively related to soil Zn and mineralizable N. Response of starch concentration was negatively related to Olsen STP, soil OM, and soil NO_3–N. Corn starch concentrations have been related most strongly to N availability, with starch content tending to decrease as N availability increases (Marschner, 1995). Response of protein concentration was positively related to soil NO_3–N, and negatively related to soil pH values. Availability of both N and S has been directly related to protein content in corn (Marschner, 1995).

Soybean Yield and Quality

When averaged across all residual fertilizer treatment effects and soil variability, soybean yield was not significantly affected by starter fertilizer application. However, yield response to starter fertilizer exhibited spatial correlation (Fig. 4-3) and differed on a site-specific basis. Yield response was negatively correlated to absolute yield level, although this correlation was weak (Fig. 4-4). Soybean yield response to starter fertilizer was negatively related to Olsen STP, total organic C, and OM, and positively related to soil test K (Table 4-3). Phosphorus was by concentration the single largest component of the starter treatment, and greater responses to fertilizer P at low STP values are consistent with the overall trends of yield response to P that we observed in the data (Fig. 4-5). However, there was no significant difference in the critical value for Olsen STP between starter fertilizer treatments (Fig. 4-5). Addition of starter appeared to allow utilization of higher levels of soil test K. The negative relationship between soybean response to starter and soil OM which we observed was previously reported by Bly et al. (2001). In that study, low soil OM was associated with low S availability. Reasons for the negative relationship between response to starter and total soil C are not clear.

Starter fertilizer application resulted in small but significant increases in soybean protein concentration (1.76 g kg^{-1}, 0.4% increase) and decreases in soybean oil concentration (2.36 g kg^{-1}, 1.1% decrease). Overall, responses of seed protein concentration to starter were indirectly related to absolute levels of seed protein concentration (Fig. 4-4). Positive protein concentration responses were associated with low levels of soil test Zn, high soil pH values, and treatments that had received higher N rates in the previous season. While we did not collect data on residual NO_3–N following corn harvest, the highest N rates used in this experiment have been associated with higher levels of residual soil NO_3–N (Jokela and Randall, 1988; Randall and Mulla, 2001). Sulfur and nitrogen are both essential to soybean seed protein synthesis (Hitsuda et al., 2008). There is some evidence that these nutrients interact in regulating seed-protein concentration, with higher S availability allowing more protein synthesis at higher N levels (Nakasathien et al., 2000). We observed larger soybean protein increases in response to S supplied through starter fertilizer in those plots where we would expect higher levels of residual N. Zinc nutrition is also essential to protein synthesis in soybeans (Marschner, 1995), and protein responses to starter were highest when soil Zn availability was lowest. The mechanism explaining higher responses to starter at high soil pH values is not known. Larger positive responses of seed oil concentration to starter fertilizer were associated with higher levels of Olsen STP and lower levels of soil test K. These were the same conditions where we observed the lowest absolute soybean seed oil concentrations. As with seed protein, the responses of seed oil concentration to starter fertilizer were inversely proportional to levels of absolute seed oil concentration (Fig. 4-4).

SUMMARY AND CONCLUSION

Application of N-P-S-Zn starter fertilizer to corn resulted in overall yield increases. Response varied on a site-specific basis and differed across N and P fertility levels. We observed synergistic interaction between N and P fertility and starter fertilizer. Response was also related to Zn deficiencies; however, our methods did not allow quantitative determination of the individual effects of the N, P, S, and Zn components of the starter. Starter fertilizer application increased corn protein and oil concentrations, and responses varied across fertility levels and soil parameters. Starter fertilizer application affected soybean protein and oil concentrations, but yield increases were observed only at low values of STP and soil OM. Potential may exist for optimizing use of starter fertilizer through site-specific application.

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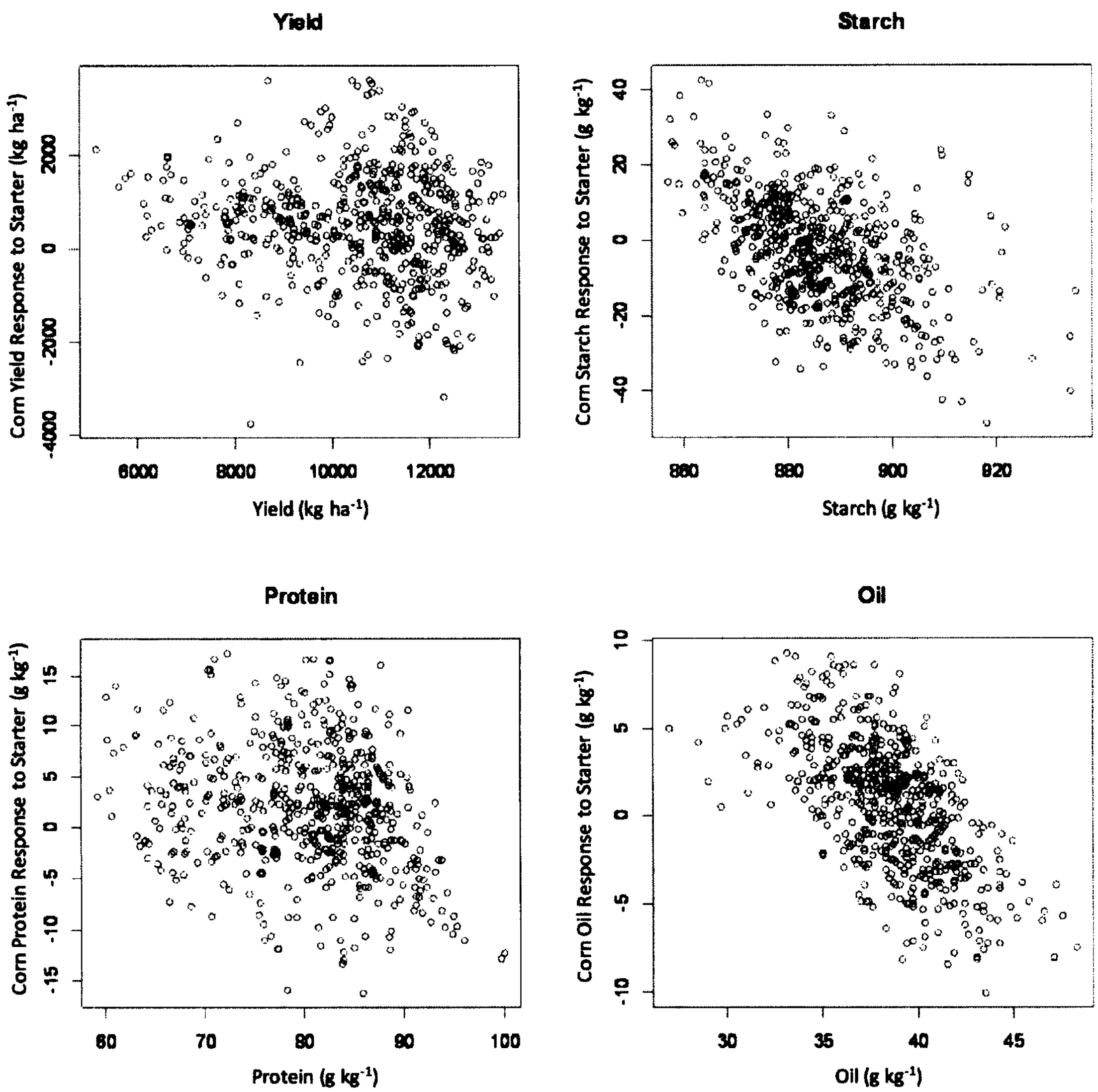

Fig. 4-1. Responses of corn yield, starch, protein, and oil to N-P-S-Zn starter fertilizer plotted against yield, starch, protein, and oil in untreated plots. A significant negative correlation existed in all cases. Correlation was weakest for corn yield (ρ=-0.12), strongest for starch (ρ=-0.52) and oil (ρ=-0.61) concentrations, and intermediate for protein concentration (ρ=-0.23).

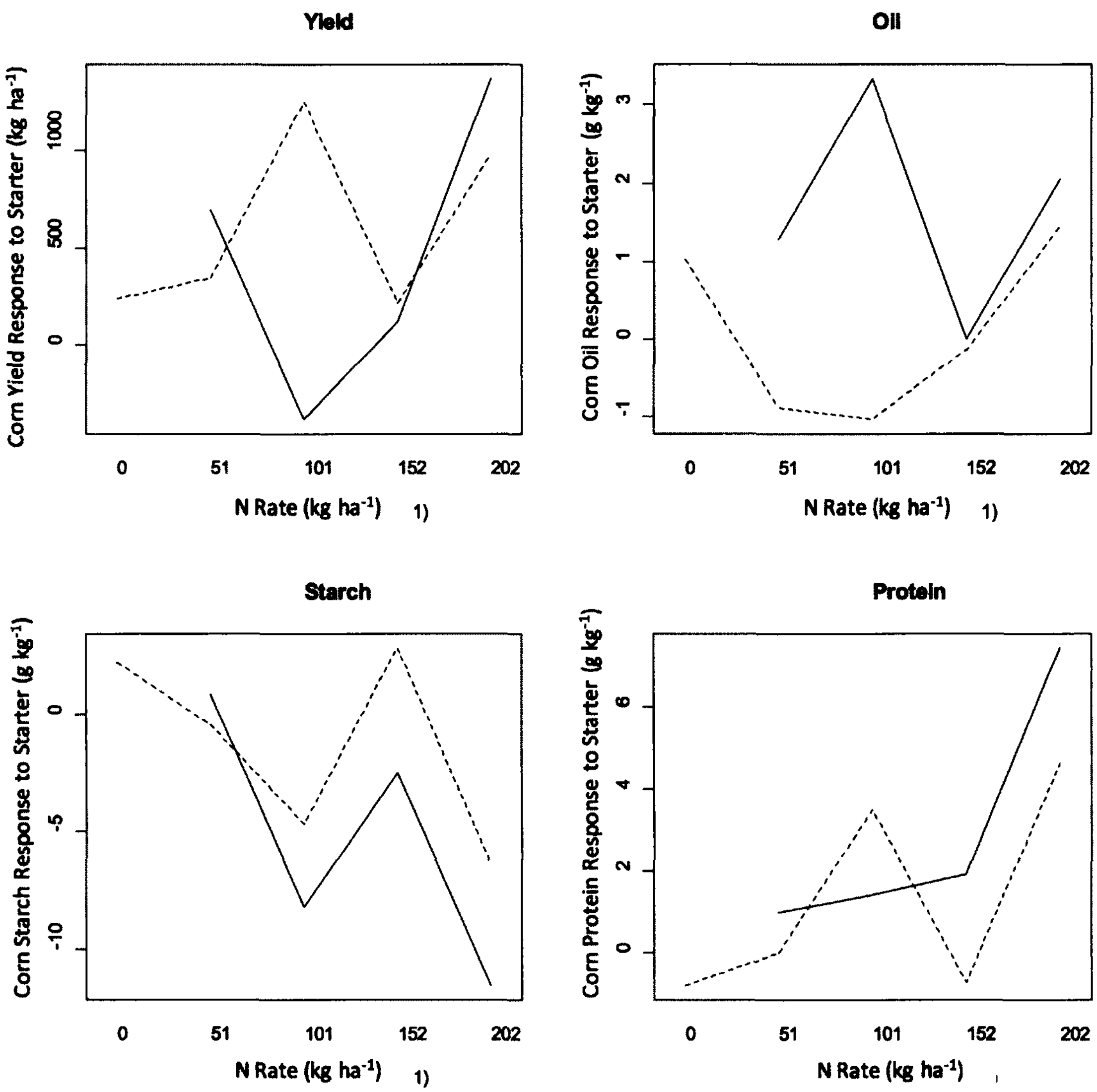

Fig. 4-2. Response of corn yield and oil, starch, and protein concentration to N-P-S-Zn starter fertilizer across nine combinations of N and P fertilizer rates. Dashed line indicates responses at 0 kg ha^{-1} P; solid line indicates responses at 56 kg ha^{-1} P.

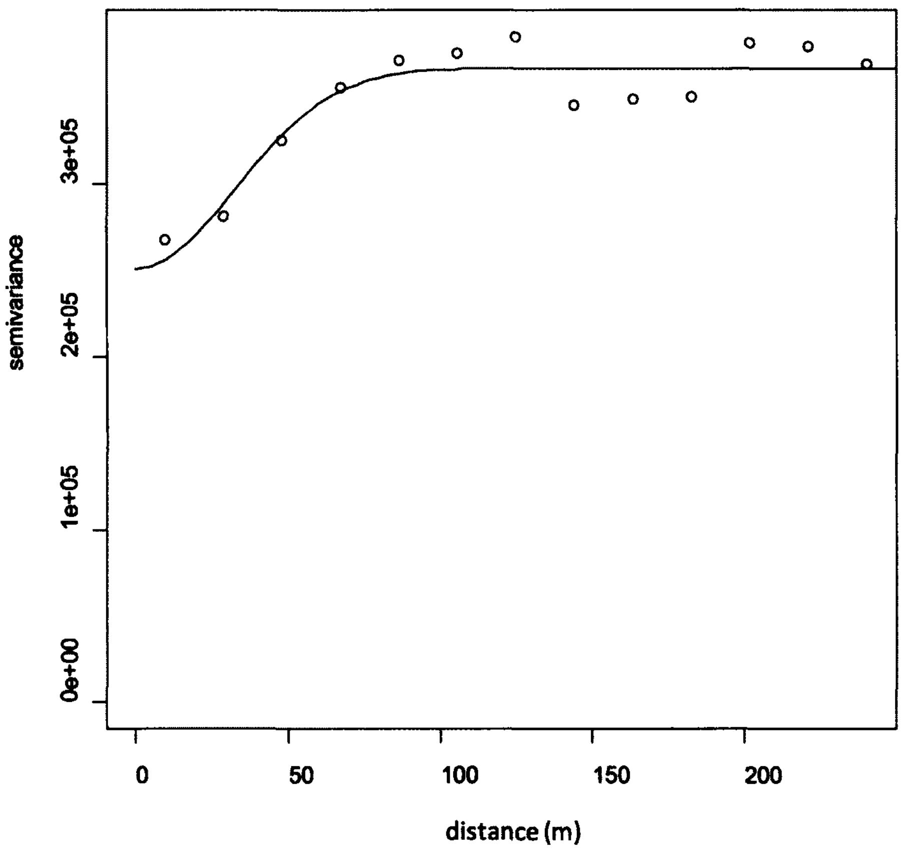

Fig. 4-3. Semivariogram of soybean yield response to N-P-S-Zn starter fertilizer. Yield response exhibited spatial autocorrelation at distances less than 100 m.

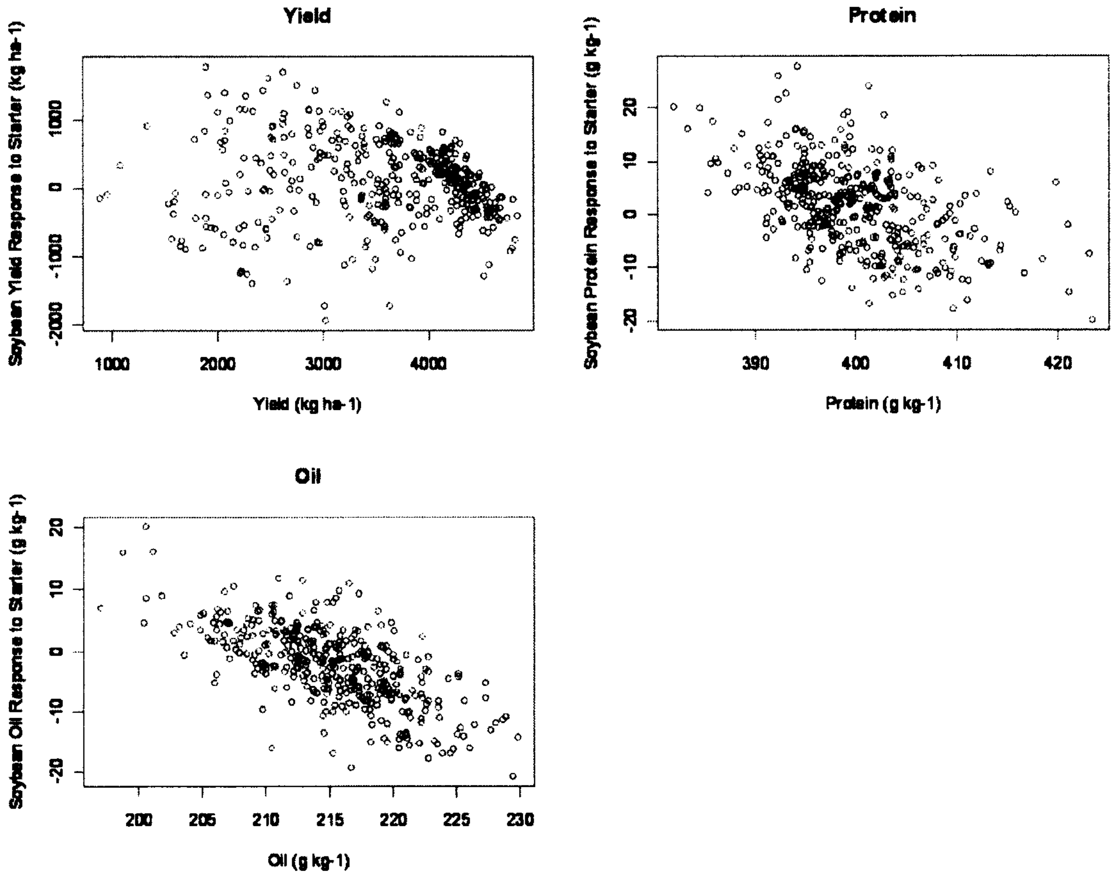

Fig. 4-4. Responses of soybean yield, protein, and oil to N-P-S-Zn starter fertilizer plotted against yield, protein, and oil in untreated plots. A significant negative correlation existed in all cases. Correlation was weakest for soybean yield (ρ=-0.12) and strongest for protein (ρ=-0.51) and oil (ρ=-0.66) concentration.

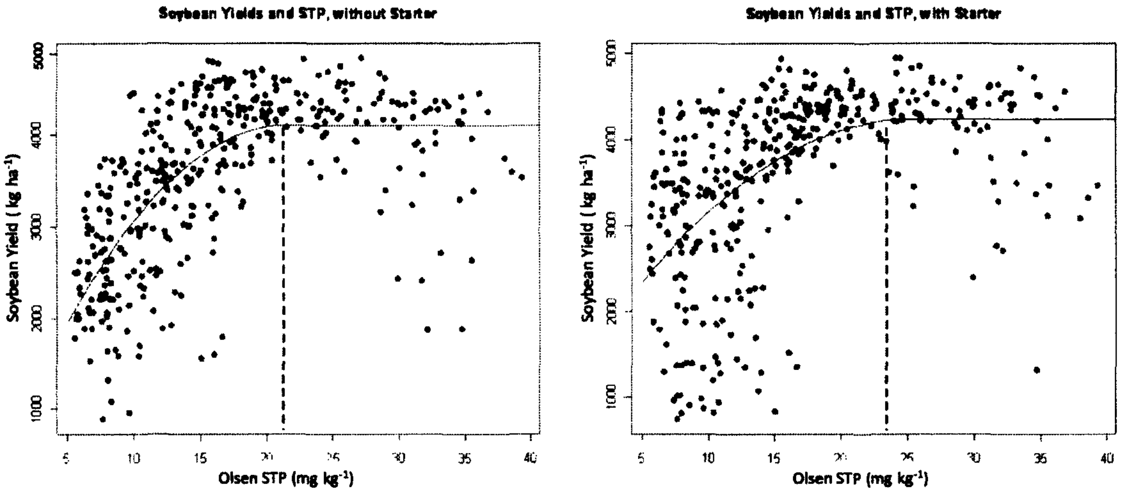

Fig. 4-5. Soybean yield response to soil test phosphorus (STP) without N-P-S-Zn starter (left panel) and with N-P-S-Zn starter fertilizer (right panel). Vertical dashed line indicates critical STP value for soybean yield. Application of 28 kg P ha^{-1} as starter did not significantly affect the critical STP value for soybean yield.

Table 4-1. Parameter estimates for soil variables significantly related to corn yield response to N-P-S-Zn starter fertilizer across all rates of fertilizer N and P. Positive coefficients indicate that corn yield response increased as the levels of the variable increased; negative coefficients mean that corn yield response decreased as the levels of the variable increased.

Variable	Estimate	Standard Error	P>t
Olsen P (mg kg^{-1})	30.57	15.58	*
Zn (mg kg^{-1})	-496.03	119.96	***
pH	508.62	158.04	**
PBMN† (kg ha^{-1})	4.51	1.07	***

*Significant at 0.05 probability level.
**Significant at 0.01 probability level.
***Significant at 0.001 probability level.
†Phosphate-borate mineralizable nitrogen.

Table 4-2. Parameter estimates for soil variables significantly related to corn yield response to N-P-S-Zn starter fertilizer at the highest level of fertilizer N applied (202 kg ha^{-1}). Positive coefficients indicate that corn yield response increased as the levels of the variable increased; negative coefficients mean that corn yield response decreased as the levels of the variable increased.

Variable	Estimate	Standard Error	P>t
P rate (kg ha^{-1})	3.15	544.82	†
Zn (mg kg^{-1})	-1136.54	237.68	***
PBMN‡ (kg ha^{-1})	4.28	1.36	**
NO_3–N (kg ha^{-1})	17.11	4.38	***

**Significant at 0.01 probability level.
***Significant at 0.001 probability level.
†Significant at 0.1 probability level.
‡Phosphate-borate mineralizable nitrogen.

Table 4-3. Parameter estimates for soil variables significantly related to soybean yield response to N-P-S-Zn starter fertilizer. Positive coefficients indicate that soybean yield response increased as the levels of the variable increased; negative coefficients mean that corn yield response decreased as the levels of the variable increased.

Variable	Estimate	Standard Error	P>t
Olsen P (mg kg^{-1})	-20.36	4.73	***
K (mg kg^{-1})	5.37	2.17	*
Organic Matter (%)	-216.73	41.4	***
Total Organic C (kg ha^{-1})	-65.19	14.34	***

*Significant at 0.05 probability level.
***Significant at 0.001 probability level.

CHAPTER 5: Corn Protein, Starch, and Oil Composition in a Nitrogen and Phosphorus Fertilizer Experiment[1]

ABSTRACT

Corn [*Zea mays* L.] protein, starch, and oil composition contribute substantially to the value realized in corn by the end-user. Our objectives were to characterize spatial variation in corn grain protein, starch, and oil composition in two south-central Minnesota fields over 6 yr of a corn–soybean [*Glycine max* (L.) Merr.] rotation, and to determine the influence on corn quality of N and P fertilizer treatments, soil chemical properties, and topography. Mean values of corn protein, oil, and starch concentrations differed significantly by site-year. Protein concentration increased in response to increasing N rates in all 6 site-years, and decreased in response to P addition in 3 of 6 site-years. Starch concentration decreased in response to increasing N rates in 5 of 6 site-years. Starch concentration responded to an N x P interaction effect in 3 of 6 site years, with starch concentration responding more positively to P at low rates of N. Oil concentration was least responsive to N and P, and observed responses were variable. Corn quality parameters exhibited spatial autocorrelation, but the spatial patterns of corn quality varied across years. Protein and starch concentrations were more consistently related to soil P than to any other soil variable. Field-average starch and protein concentration may be influenced through N and P fertilizer rates, but temporal variability in the spatial patterns of corn quality suggests little opportunity for predictive site-specific management.

Abbreviations: AIC, Akaike Information Criterion; AN, Nicollet County site; DEM, digital elevation model; PBMN, phosphate-borate mineralizable N; WB, Brown County site

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INTRODUCTION

Although the value of corn is expressed in the United States on a dollar per bushel basis, it is the composition of corn that generates economic value for the end-user. Specific end-users prefer uniform corn quality in order to optimize consistency of both the processing and of the end-product (Watson, 1987). However, the desired corn quality traits may vary considerably, depending on the particular end-user. High protein and oil concentrations are desirable for processors producing livestock feed, high starch concentrations are desirable for ethanol producers, and low protein and high starch and oil are desirable for wet-mill food ingredient processors (Hurburgh, 1997).

Multiple factors influence the components of corn quality, including genetics (Bullock et al., 1989), climate (Earle, 1977), and soil properties (Nugteren, 1999). Most research has indicated corn protein concentration to increase in response to N fertilization (Miao et al., 2006b; Sauberlich et al., 1953; Tsai et al., 1992; Zhang et al., 1993). Research has shown varied responses of corn oil concentration to N fertilization, including positive responses (Welch, 1969), negative responses (Miao et al., 2006b), or no significant relationship (Singh et al., 2005; Zhang et al., 1993). Corn starch concentration has been found to decline in response to N fertilization (Miao et al., 2006b; Singh et al., 2005). Welch (1969) found a positive effect of fertilizer P and K application on corn oil concentration. A positive relationship has been reported between K fertility and corn protein concentration (Usherwood, 1985; Yang et al., 2004).

While relationships between fertilizer rates and corn quality have been described, significant variability exists in corn protein, oil, and starch concentrations within fields under uniform management (Hopkins, 2001; McNeill et al., 2005; Miao et al., 2006a, Singh et al., 2005). The causes of within-field variability in corn quality are not known. However, both McNeill et al. (2005) and Miao et al. (2006a) observed spatial autocorrelation in corn protein and starch concentration, indicating that variability in these quality parameters could be related to spatially dependent variability in soil properties and amenable to site-specific management. Hao et al. (2010) observed significant spatial autocorrelation in corn grain ethanol yield in two years and found soil and topographical difference explained most of the variability in ethanol yield in one of these years. Miao et al. (2006a) emphasized the need for more research to evaluate temporal stability in the spatial patterns of grain quality and to determine the causes of observed spatial patterns.

To address the need for better understanding of the nature and causes of variation in corn quality, we established a 6-yr field experiment at two sites in southern Minnesota. Our objectives were (i) to characterize corn protein, oil, and starch concentration and their variability within fields, between sites, and across years; (ii) to determine the effects of N and P fertilizer applications on corn quality; and (iii) to identify those site characteristics most related to corn quality.

MATERIALS AND METHODS

Site Description

Experiments were established in the fall of 2001 on two 16-ha fields in south-central Minnesota. The two fields are located in Nicollet County (AN site, 44°23'N, 94°08'W) and Brown County (WB site, 44°08'N, 94°41'W). The sites were initially developed for agriculture in the 1860s, and have been in a corn–soybean rotation since the 1960s. We chose sites without a history of manure application within the previous 5 yr in order to minimize effects of residual manure on the soil nutrient and mineralization tests. The soils at the AN site lie within a Clarion–Canisteo–Webster association, and consist of the of Canisteo series (fine-loamy, mixed, superactive, calcerous, mesic Typic Endoaquolls), Harps series (fine-loamy, mixed, superactive, mesic Typic Calciaquolls), Le Sueur series (fine-loamy, mixed, superactive, mesic Aquic Argiudolls), Cordova series (fine-loamy, mixed, superactive, mesic Typic Argiaquolls), Okoboji series (fine, smectitic, mesic Cumulic Vertic Endoaquolls), and Lester series (fine-loamy, mixed, superactive, mesic Mollic Hapludalfs) (Jackson, 1994; USDA-NRCS, 2011). The soils at the WB site lie within a Nicollet–Clarion–Webster association, and consist of the Canisteo series, Clarion series (fine-loamy, mixed, superactive, mesic Typic Hapludolls), Nicollet series (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Okoboji series, and the Fieldon-Canisteo complex (fine-loamy to coarse-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) (Christensen, 1988; USDA-NRCS, 2011). Soils at both sites formed from calcareous glacial till. The AN site is systematically tile drained on 30-m spacings; the WB site has limited tile drainage. Field management is typical for a corn–soybean rotation in south-central Minnesota and consisted of single-pass fall chisel-plowing or disking of soybean stubble and single-pass spring field cultivation prior to corn planting. Following corn harvest, disk-chisel tillage was used to incorporate corn residue. In each corn year, the farmer planted a single, commercial corn hybrid following typical production practices (Table 5-1). Temperature and precipitation data for the length of the experiment was obtained for weather stations near the experimental sites from the National Climatic Data Center (NCDC, 2011). Soil moisture data and solar radiation data was obtained from the University of Minnesota Climatology Working Group (CWG, 2009).

Experimental Design

The experimental design included 3 replications of 9 treatments in a split-plot arrangement of a randomized complete-block design. Phosphorus (0 and 56 kg P ha^{-1}) was the main plot; N treatments (0, 50, 101, 152, and 202 kg N ha^{-1}) were applied as anhydrous ammonia (82–0–0) in strips across the field, and placement of these strips was randomized within the P treatments. Because diammonium phosphate (DAP, 18–46–0) was used as the P source, there was no 0 kg N ha^{-1} treatment within those plots where P was applied. The DAP rate provided N at a rate of 50 kg ha^{-1}. K was applied as muriate of potash (KCl) to the entire field at a rate of 93 kg K ha^{-1}. One extra 101 kg ha^{-1} N strip was included in each block to avoid having 0 kg ha^{-1} N treatments repeated on the same strip in consecutive rotations; instead, the 0 kg N ha^{-1} treatments were applied to a strip that had received a 101 kg N ha^{-1} rate in the previous N application. All other treatments were applied to the same strip in each year of application. Identical design was applied at both sites. Nutrients were applied in November of the fall prior to the corn year of the corn–soybean rotation, with the exception of the final application at site AN, where fertilizer was applied in April 2006. All fall applications of anhydrous ammonia included the nitrification inhibitor nitrpyrin (Dow Agrosciences, Indianapolis, IN). A miscalibrated N regulator resulted in anhydrous ammonia application rates being approximately 60% higher than planned at site AN in 2006, so that total N applications were 0, 80, 173, 215, and 338 kg ha^{-1} in the 0 P plots and were 50, 130, 225, and 265 kg ha^{-1} in the P plots.

Grain Quality Measurements

In the falls of 2002, 2004, and 2006, plots were harvested with a modified Model 8 Massey Ferguson plot combine (AGCO Corp., Duluth, GA). This combine was equipped with an electronic ground distance monitor and a computerized HarvestMaster weigh cell (HarvestMaster, Logan, UT). Harvest measurements were taken from two corn rows in the center of 15-m subplots along selected 9-m wide transects in each field. These 15-m sections corresponded to the 0.014-ha soil sampling grid cells. Transects were selected to obtain data from all combinations of N and P rates. In 2004 at site AN, 9 extra replicate strips were harvested; small areas of the experiment were not harvestable at site AN in 2002 and site WB in 2006. At site AN, 574, 792, and 594 individual subplots were harvested in 2002, 2004, and 2006, respectively; at site WB, 621 subplots were harvested in 2002 and 2004 and 614 subplots were harvested in 2006. The grain harvested from the 15-m length of each subplot was weighed and yield was determined at 15.5% moisture. Grain samples were retained from each subplot and were analyzed for protein, oil, and starch concentration using near infrared spectroscopy, using a Foss Infratec 1229 spectrometer (Foss, Hillerød, Denmark) in years 2002 and 2004, and a Perten DA7200 spectrometer (Perten Instruments AB, Segeltorp, Sweden) in 2006. Protein, oil, and starch concentrations are reported on a g kg^{-1} dry weight (0% moisture) basis.

Soil Chemical and Topographical Variables

The soil sampling and analysis protocol is described in detail by Anthony et al. (2012). Briefly, soils were sampled in the fall of each year 2001–2007. Samples were taken from 9- by 15-m (0.014-ha) grid cells along a subset of the 36 transects of the N plots. In the falls of 2001 – 2004, 6 transects were sampled, totaling 132 samples per year at site AW and 138 samples per year at site WB. In the falls 2005–2007, 12 transects were sampled, totaling 264 samples per year at site AN and 276 samples per year at site WB. In the fall of 2001, 0- to 15-cm samples from each cell were analyzed for Bray P, Olsen P, K, pH, organic matter, and Zn; 0- to 60-cm samples from each cell were analyzed for total organic C, total Kjeldahl N, NH_4–N, NO_3–N, and mineralizable N. To determine mineralizable N, we used the phosphate borate mineralizable N (PBMN) test described by Gianello and Bremner (1988) as modified by Clay and Malzer (1993). In all falls following, 0-15 cm samples were analyzed for Bray P, Olsen P, K, and pH. In odd-numbered falls following, which were subsequent to the soybean harvest and preceding the corn year in the rotation, 0-60 cm samples were taken and analyzed for NH_4–N, NO_3–N, and mineralizable N. Soil test values for grid cells which were not sampled in a particular year were estimated using cokriging in the Spatial Analyst extension of Arc View 9.3 (Environmental Systems Research Inst., Redlands, CA,). Soil test values for each 0.014-ha grid cell were extracted as the cell mean from kriged rasters and used for further analysis.

Elevation and position measurements were made on each field using survey grid GPS (horizontal accuracy +/- 0.5 m) and land-based laser (vertical accuracy +/- 0.05 m). Elevation measurements were made on a semi-regular grid with mean distance between points of approximately 20 m. These coordinates were used to create a digital elevation model of the fields using kriging in the Spatial Analyst extension of ArcView 9.3. The DEM raster was used to generate slope, curvature, and aspect rasters using these respective tools in the ArcView Spatial Analyst. The Fill, Flow Direction, and Flow Accumulation tools of the Arc View 9.3 Spatial Analyst extension were used to derive a hydrologic flow accumulation raster for each field. Mean values of the elevation, slope, curvature, aspect, and flow accumulation for each 0.014-ha grid cell of the field were extracted and used in further analysis.

Statistical Analysis

To determine significance of N and P treatments, we conducted a split-plot analysis of variance using the aov procedure in R version 2.12.1 (R Development Core Team, 2010). To maintain a balanced design, analysis was conducted only on N rates that were in common between P treatments, which excluded the 0 kg ha^{-1} N rate in this analysis. To accommodate analysis of variance for data from site AN in 2006, where erroneous N rates were applied, N treatments were assigned a factorial order of 1–4 in order to coerce the rates into a balanced design. We used geostatistics to analyze the spatial structure of variability in corn quality components. When necessary, data was log-transformed in order to normalize the distributions and most closely meet the assumption of intrinsic stationarity. Sample variograms were calculated and were fitted with exponential, spherical or gaussian models using weighted least-squares regression (Cressie, 1993); models were selected to minimize the Akaike information criterion (AIC). Values were estimated for the variogram range, sill, and nugget. The proportion of variance in the data attributable to spatial correlation was characterized by the ratio of structural variance (sill-nugget) to the sill. Geostatistical analysis was conducted using the geoR package (Ribeiro and Diggle, 2001) for R version 2.12.1 (R Development Core Team, 2010). Temporal stability of corn quality was determined using the ranked correlation technique described by Lamb and Rehm (2002), in which correlations are determined between variables at ordered locations. To evaluate relationships between soil variability and corn quality, we calculated correlation coefficients between each soil variable and corn protein, oil, and starch concentration for all site-years. In order to avoid confounding effects of fertilizer treatments, we calculated these correlations using only a subset of the data in which N rates were greater than 120 kg ha^{-1}, which represents typical production practices in south-central Minnesota. Data from both P rates were included in the analysis. Multiple comparison tests indicated that treatment differences were rarely significant among this subset of data. To determine interrelationships among corn quality parameters, correlation coefficients were calculated between corn protein, oil, and starch concentrations for data collected within the same site-year. Correlations were determined using the cor procedure in R version 2.12.1 (R Development Core Team, 2010).

RESULTS AND DISCUSSION

Weather Variation

Growing season conditions in southern Minnesota were warm and dry in 2002. Growing-degree units were above normal, but solar radiation was below normal. A cool May was followed by much above normal temperatures in June and July, with 11 days exceeding 32 °C in these two months. August temperatures were near normal, and September temperatures were above normal. Growing season precipitation was below normal. July was particularly dry, and soil moisture on 1 August was considerably below normal. This year was particularly dry at site WB. The 2004 growing season was persistently cool and damp, with below normal growing degree units and below normal solar radiation. Temperatures in the months of May through August were slightly below normal, but were followed by a warm September. April precipitation was below normal, but the months of May through July had much above normal precipitation, and soils were approaching 100% of water-holding capacity on 1 August. This year was particularly wet at site AN. The 2006 growing season had above normal growing degree units and normal solar radiation. Temperatures were above normal from April through August, with a particularly large departure from normal temperatures in July. September was cool. Growing season precipitation was very close to the long-term mean, and large departures from normal precipitation were not observed in any month. Soil moisture on 1 August was above normal.

Corn Quality Variation by Site and Year

Across all sites, years, and fertilizer treatments, mean corn protein (81.8 g kg^{-1}) and oil (37.7 g kg^{-1}) concentration was slightly lower and mean starch concentration (724.9 g kg^{-1}) was slightly higher than published national values (95.0, 43.0, and 717 g kg^{-1}) (NRC, 1982) and values for contemporary corn quality research in Minnesota (91.0, 42.1, and 714 g kg^{-1}) (Belyea et al., 2004). Corn protein, oil, and starch concentration varied significantly across years and between sites (Table 5-2). Corn quality was relatively consistent between sites in 2002. Protein and oil concentrations were very high at both sites in this year (Fig. 5-1 and 5-2) and starch concentration was low. Protein and oil concentrations were lower at both sites in 2004, while starch concentrations were higher at site AN only. In 2006, protein concentrations were low and starch concentrations were high at site WB. Mean yields for each field were lowest in 2002, averaging 9939 and 9317 kg ha^{-1} at sites AN and WB, respectively. Mean yields for each field were highest in 2006, averaging 12313 and 10629 kg ha^{-1} at sites AN and WB, respectively. In 2004, mean yields at sites AN and WB were 11834 and 10344 kg ha^{-1}. Comparing across years, we observed a general trend of yield being directly related to starch concentration and inversely related to oil and protein concentration.

Corn Quality Response to N and P fertilizer

Corn protein concentration exhibited significant positive response to N fertilizer rate in all years (Table 5-3, Fig. 5-1 and 2). The degree of response varied significantly between sites and across years. We observed the smallest response at both sites in 2002, the year of highest protein concentration. The response curves were steeper in 2004 and 2006. Application of P had a significant effect on corn protein concentration in 3 of 6 site-years. Phosphorus application resulted in lower protein concentration in each of these cases. A significant N x P interaction effect was observed at both sites in 2004 and 2006. The negative effect of P on protein concentration was more pronounced at lower N rates at site AN in 2004 and at both sites in 2006, resulting in steeper N response curves in the P treatments. No response to P or N x P interaction was observed at either site in 2002. Protein responses to N were linear in 2002, but curvilinear in 2004 and 2006.

Corn oil concentration was significantly affected by N rate in 5 of 6 site-years, by P rate in 2 of 6 site-years, and by N x P interaction in 5 of 6 site-years (Table 5-3). Both positive and negative responses to N and P were observed, depending on site and year. Differences between P treatments tended to be greatest at lower rates of N (Fig. 5-1 and 2). Of the three quality parameters observed in this experiment, oil concentration was least responsive to N and P fertilizer.

Nitrogen fertilizer rate significantly affected corn starch concentration at all site-years (Table 5-3), but responses differed significantly across sites and between years. In 5 of 6 site-years, higher N rates resulted in lower starch concentration. However, at site WB in 2002 higher N rates resulted in higher starch concentration. In the droughty conditions experienced at this site in 2002, greater vegetative growth associated with high N rates could have resulted in more drought stress in these treatments, potentially impacting starch response. We are not aware of other reports of a positive response of starch to N, as the literature consistently reports negative responses of corn starch concentration to N fertilizer (Miao et al., 2006b; Singh et al., 2005). Significant responses to N x P interaction were observed in 3 of 6 site-years. Differences between P treatments tended to be greatest at lower rates of N and starch concentrations were higher in treatments receiving 56 kg ha^{-1} P.

Spatial Autocorrelation in Corn Quality

Corn quality parameters exhibited varying spatial dependence (Table 5-4; Fig. 5-3 and 5-4). The observed ranges of spatial dependence exhibited consistency by site-year. The range of spatial dependence for all parameters was greatest at site AN in 2004 and least at site WB in 2006. On average, over 50% of variance in corn quality was spatially correlated. We observed a higher amount of spatial dependence in corn quality than reported by Miao et al. (2006a). This could be accounted for by a more dense sampling design in our experiment. Because the observed spatial dependence in both studies decreased with increasing separation distance, more dense sampling could allow detection of high spatial autocorrelation at short separation distances that would otherwise remain unobserved. No single corn quality parameter tended to exhibit more spatial dependence than others. In contrast to Miao et al. (2006a), we observed spatial dependence in oil concentration in 5 of 6 site-years. The presence of spatial correlation suggests that corn quality is related to site-specific soil variability and could be managed through site-specific techniques.

Previous investigations of spatial dependence in corn quality (Miao et al., 2006a; McNeill et al., 2005) have relied on hand-harvesting of <10 individual ears of corn at each sampling point. McNeill et al. (2005) also determined corn quality across ears at single locations and found substantial variations within location. McNeill et al. (2005) concluded that site-specific management of corn quality through segregation on the combine during grain harvest would not be feasible due to this variation within location. In our research, corn quality values represent integrated samples from the 15-m length of our subplots, which is similar to the harvest distance integrated in the grain flow of modern corn harvesters. Our finding of significant spatial autocorrelation with this sampling scale indicates that grain segregation on the combine during harvest could be reconsidered as a means to obtain additional economic value in corn production.

Corn Quality and Soil Variability

Although significant correlations were found between soil variables and corn quality parameters in 5 of 6 site-years, very few consistencies in these relationships existed between sites or across years (Table 5-5). Soil test P was positively correlated with protein concentration at both sites in 2002, but was negatively correlated with protein concentration at both sites in 2004 and 2006. Soil P was positively correlated with starch concentration at both sites in 2004 and 2006. Significant positive correlation existed between soil pH and oil concentration in 3 of 6 site years, but pH was not significantly related to oil concentration in the other 3 site-years. In 2002 at site WB, we observed a strong positive correlation between starch concentration and both elevation and slope. Higher elevations and steeper slopes have been associated with lower water-holding capacity, providing another line of evidence that starch concentration may be higher in water-stressed conditions. Higher starch concentrations tended to be associated with higher elevation and steeper slope when relationships were significant. This observation contrasts with the findings of Nugteren (1999), who reported higher starch concentrations in lower landscape positions. Many other soil variables were significantly related to crop quality parameters only in single site-years. The absence of temporally persistent relationships between soil chemical and topographical variables and corn quality parameters suggests that the observed spatial correlation in corn quality is instead related to variability in unobserved soil characteristics or to complex interactions between climate, soil, and hybrid.

Temporal Variation in the Spatial Pattern of Corn Quality

Maps of corn protein, oil, and starch concentrations showed well-defined spatial patterns for all site-years, providing visual confirmation of the geostatistical analysis. However, the spatial patterns of corn quality parameters exhibited little temporal consistency (Table 5-6). The spatial pattern of protein concentration was positively correlated across years at site WB, but in all other cases the spatial patterns in corn quality were inconsistent from year to year. These results provide additional confirmation that corn quality was not immediately related to the soil chemical and topographical variables which we observed, all of which exhibited temporal consistency in their spatial patterns (Anthony et al., 2012), or to other unobserved soil parameters that are temporally static.

Interrelationships among Corn Quality Parameters

Across all rates of N and P and across soil variability, we observed no consistent relationship between oil concentration and protein concentration (Table 5-7). Oil concentration and starch concentration exhibited consistent negative correlation. Negative correlations between protein concentration and starch concentration tended to be even stronger than the oil-starch correlations, with the exception of site WB in 2002. Singh et al. (2005), in a single site-year experiment, also reported a strong negative correlation between protein and starch concentration, a somewhat less strong negative correlation between oil and starch concentrations, and a weak correlation between oil and protein concentrations. In our experiment, the strength of the correlations between corn quality parameters was similar when calculated using data from 0 and >120 kg ha^{-1} N fertilizer treatments to the correlations calculated using fertilizer treatments (Table 5-7). This indicates that the relationships between corn quality parameters are related not only to the fertilizer effects shown in Fig. 5-1 and 2, but are also physiological characteristics of these corn hybrids that also hold true across other sources of environmental variability.

Corn protein concentration was positively correlated with observed corn yields at all 6 site-years (Table 5-7). This correlation was strongest at both sites in 2006, and was weakest at both sites in 2004. The strength of the protein-yield relationship weakened in some cases with increasing N rate, but in other cases the correlation strengthened with increasing N rate. This result contrasts with the findings of Nugteren (1999), who reported that a positive protein-yield relationship was an artifact of positive effects of N rate on both protein and yield in a single site-year experiment. Other work has reported a negative protein-yield relationship when comparisons are made across genotypes (Dudley et al., 1977; Frey, 1951). Our results suggest that within genotypes, a positive protein-yield relationship may be observed even after removing the confounding effect of N rate. We found oil concentration to be positively correlated with yield at site WB in 2006, but to be negatively correlated with yield at site WB in 2002. At the 4 other site-years, we observed no relationship between yield and oil concentration. Starch concentration was negatively correlated with yield in 4 of 6 site-years, but was positively correlated with yield at site WB in 2002. However, the yield-starch relationship differed significantly by N rate, with these differences varying by site-year. The relationships between corn yield and corn protein and starch concentration found within site-years cannot explain the relationships between mean yield and mean protein and starch concentration in comparisons across site-years, which were generally opposite. This provides additional evidence of the complexity associated with the relationships between corn quality parameters and the crop's environment.

SUMMARY AND CONCLUSIONS

The results of this experiment confirm previous research indicating positive responses of corn protein concentration to N fertilizer and negative responses of corn starch concentration to N fertilizer. In addition, we found the magnitude of these responses to vary by site and by year. In our experiment, site variation could be due either to environmental differences or to differential response between corn hybrids. Fertilizer P tended to result in lower protein and higher starch concentrations, but response was dependent on site and year. Fertilizer P effects tended to be greater at lower N rates.

Our experiment also confirmed a previous report of spatial dependence in corn quality parameters. However, we found the spatial patterns in corn quality to differ greatly between years. This temporal instability, combined with a lack of consistent relationships between corn quality parameters and soil variables, suggests that successful site-specific management of corn quality may need to be reactive rather than predictive. Segregation of corn grain on the combine is one example of such a management approach that could be effective based on relationships observed in this experiment. Segregation into two pools, one with high protein/oil and the other with high starch, is likely to provide the greatest separation of mean quality parameters. Future research should focus on other potential environmental variables and interactions that could be related to the spatial patterns in corn protein, oil, and starch concentration.

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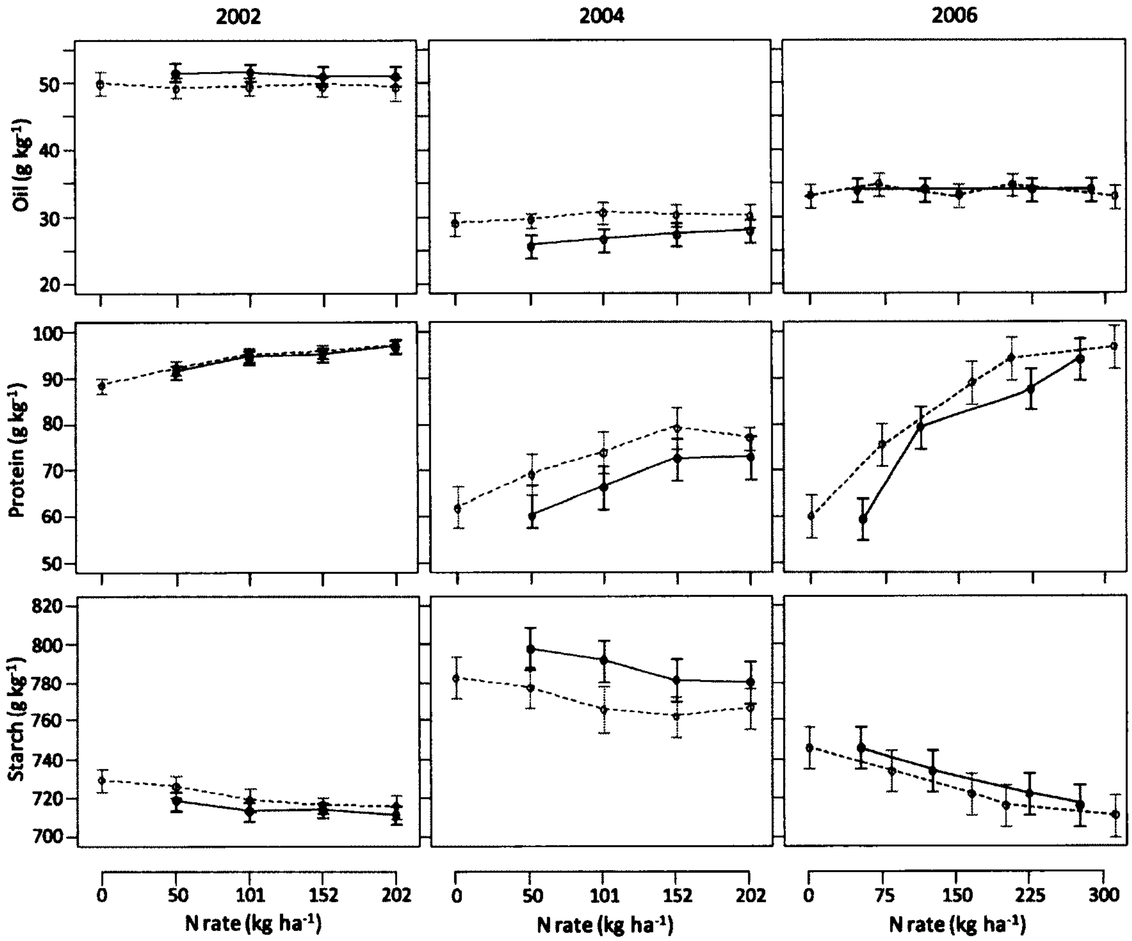

Fig. 5-1. Response of corn oil, protein, and starch concentration to N and P fertilizer treatments for site AN in years 2002, 2004, and 2006. Vertical bars represent +- Standard Error of the mean. Dashed lines and gray error bars indicate 0 kg P ha^{-1} treatments; solid lines and black error bars indicate 56 kg P ha^{-1} treatments.

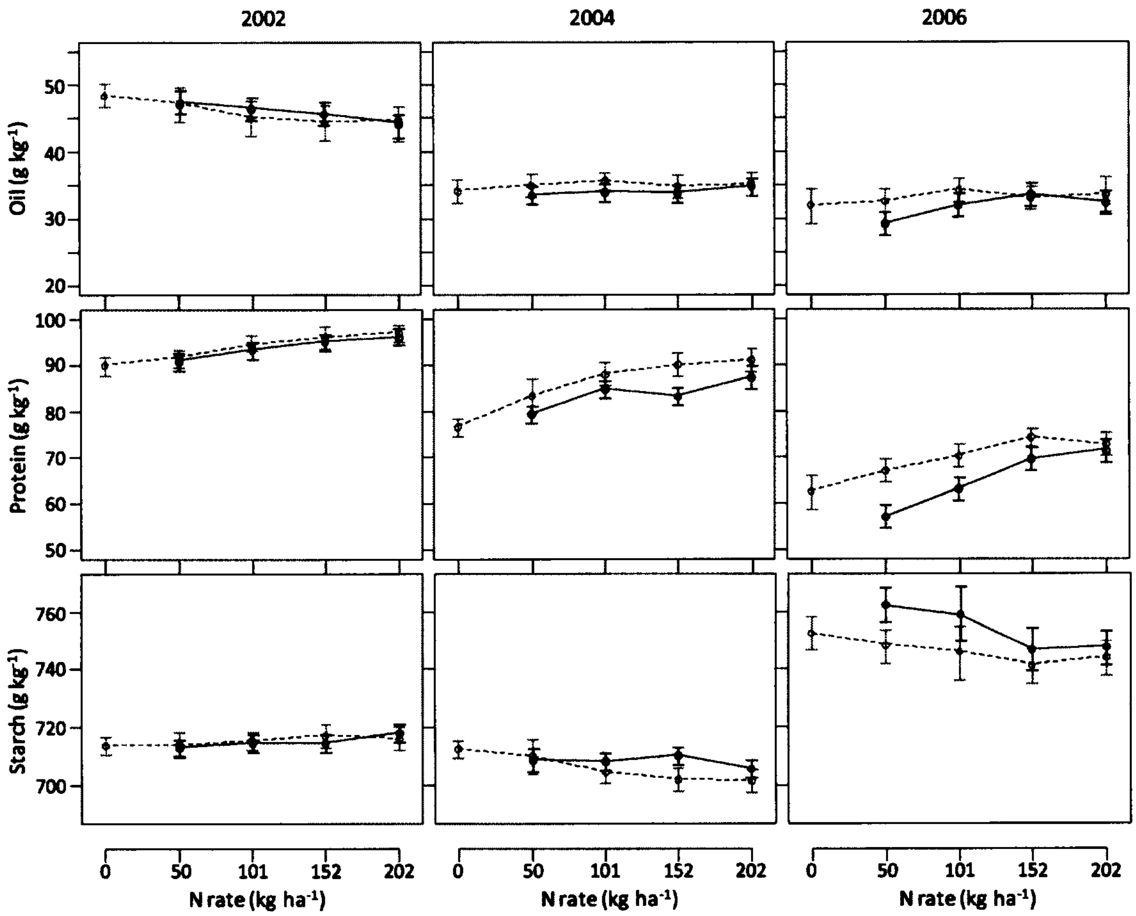

Fig. 5-2. Response of corn oil, protein, and starch concentration to N and P fertilizer treatments for site WB in years 2002, 2004, and 2006. Vertical bars represent +- Standard Error of the mean. Dashed lines and gray error bars indicate 0 kg P ha^{-1} treatments; solid lines and black error bars indicate 56 kg P ha^{-1} treatments.

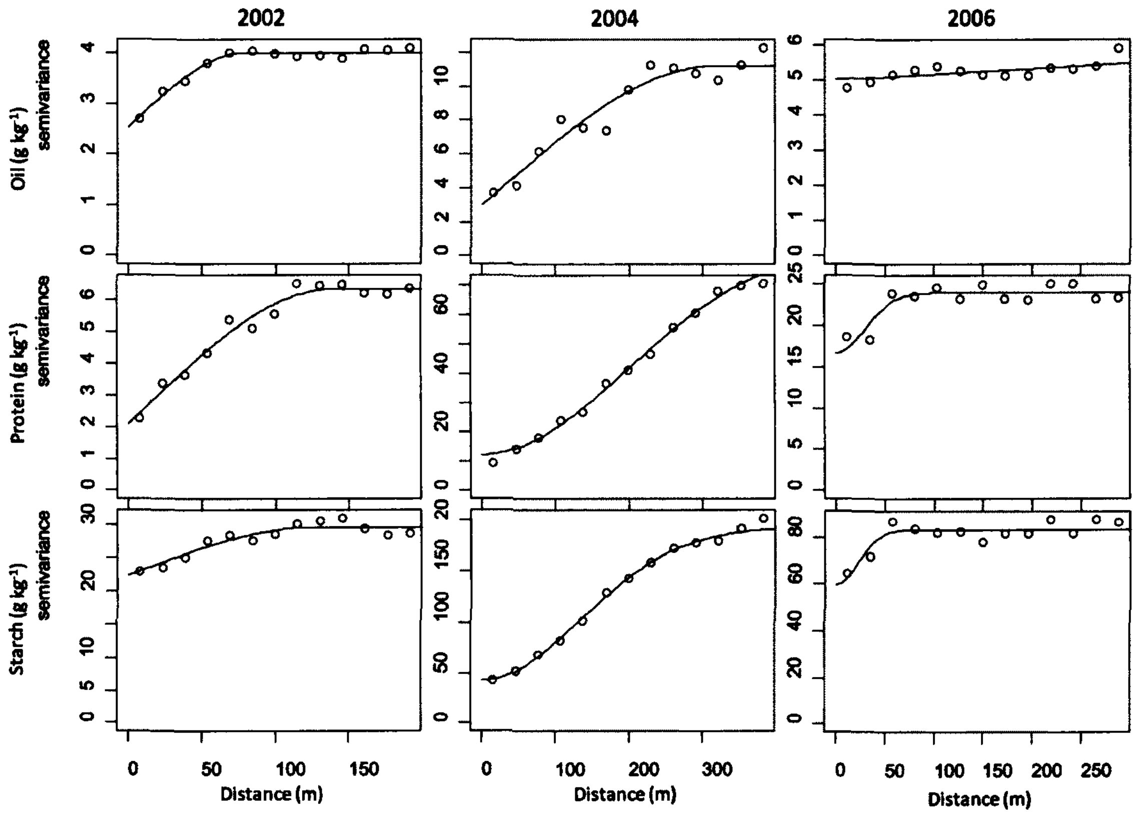

Fig. 5-3. Empirical variograms and variogram models for corn oil, protein, and starch concentration for site AN in years 2002, 2004, and 2006.

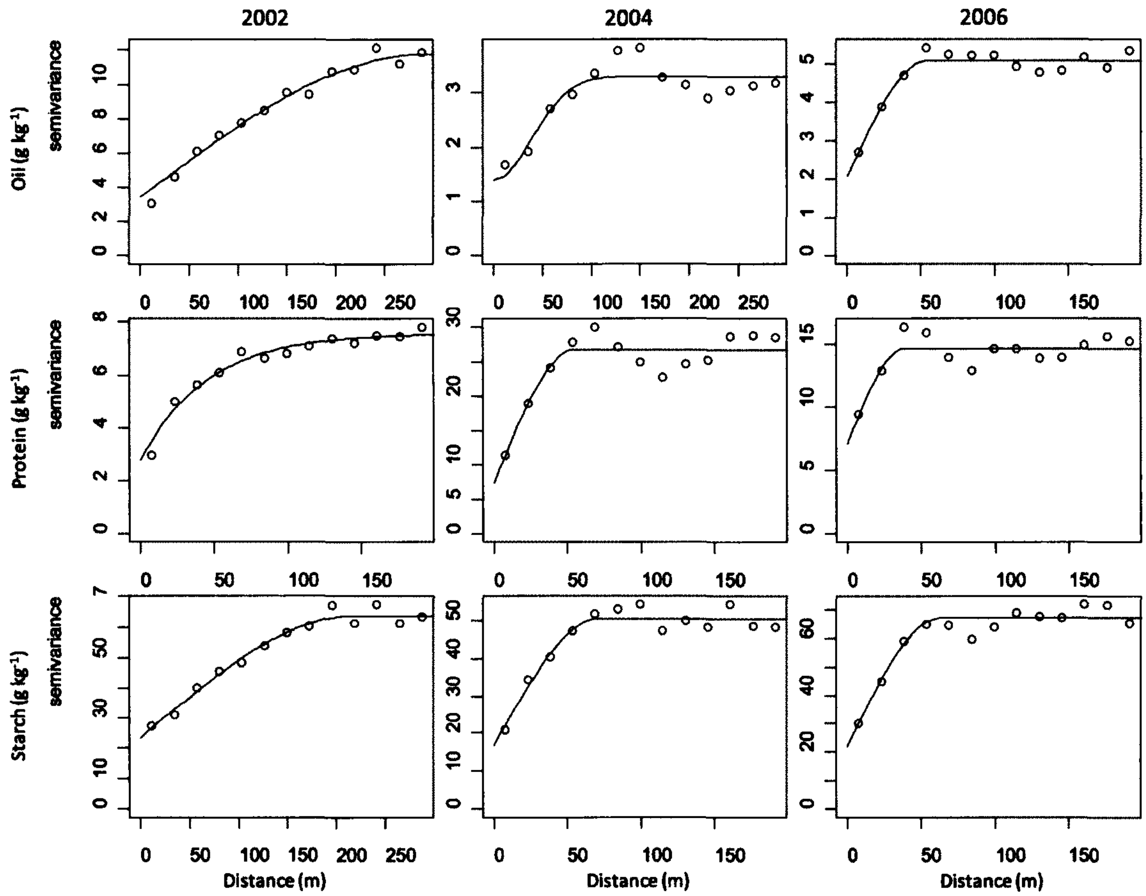

Fig. 5-4. Empirical variograms and variogram models for corn oil, protein, and starch concentration for site WB in years 2002, 2004, and 2006.

Table 5-1. Summary of agronomic information by site-year.

Site	Year	Hybrid	Population	Row Width	Planting Date
			seeds ha^{-1}	cm	
AN	2002	Pioneer 35R57	80,000	56	18 April
	2004	Dekalb 51-43	81,000	56	24 April
	2006	Dekalb 52-47	80,000	56	17 April
WB	2002	Pioneer 34G82	79,000	76	24 April
	2004	Pioneer 36N71	79,000	76	24 April
	2006	Dekalb 51-39	79,000	76	24 April

Table 5-2. Significance of year, site, and their interactions on corn protein, oil, and starch concentrations.

Source of variation	df	Protein	Oil	Starch
		p>F		
Year	2	<0.001	<0.001	<0.001
Site	1	0.528	<0.001	<0.001
Year x Site	2	<0.001	<0.001	<0.001

Table 5-3. Significance of N and P fertilizer rates and their interactions on corn protein, oil, and starch concentrations by site and year.

			Site AN			Site WB		
Year	Source of variation	df	Protein	Oil	Starch	Protein	Oil	Starch
			p>F					
2002	P	1	0.416	0.062	0.127	0.182	0.028	0.652
	N	3	<0.001	0.88	0.012	<0.001	<0.001	<0.001
	P x N	3	0.910	0.758	0.583	0.913	0.035	0.098
2004	P	1	0.028	0.046	0.059	0.093	0.231	0.058
	N	3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	P x N	3	<0.001	<0.001	<0.001	0.002	0.002	<0.001
2006	P	1	0.023	0.871	0.046	0.025	0.083	0.054
	N	3	<0.001	0.004	<0.001	<0.001	<0.001	0.002
	P x N	3	<0.001	0.005	<0.001	0.018	0.003	0.096

Table 5-4. Model variogram parameters for corn oil, protein, and starch concentration by site and year.

		Site AN		Site WB	
Year	Variable	Nugget/Sill Ratio %	range m	Nugget/Sill Ratio %	range m
2002	Oil	36.7	79.5	70.9	277.2
	Protein	67.1	139.0	63.5	135.6
	Starch	24.7	125.4	63.5	220.1
2004	Oil	73.5	317.1	57.4	94.7
	Protein	85.3	476.1	72.6	54.9
	Starch	77.5	327.1	66.9	72.0
2006	Oil	0.0	Inf.	59.2	54.1
	Protein	30.5	72.7	51.5	38.5
	Starch	28.3	55.1	67.5	62.9

Table 5-5. Correlation coefficients between corn quality parameters and soil chemical and topographical variables by site-year.†

Site	Year	Parameter	Bray P1	Olsen P	Zn	K	pH	OM‡	TOC§	NH_4–N	NO_3–N	TN¶	PBMN#	Elevation	Slope	Curvature	Flow	Aspect
AN	2002	Oil	0.04	0.05	-0.02	-0.18	-0.04	0.04	-0.01	-0.03	0.00	-0.02	-0.03	-0.01	-0.05	-0.10	0.06	0.01
		Protein	0.41	0.38	0.28	0.18	-0.39	-0.32	-0.25	0.12	-0.04	-0.12	0.25	0.41	-0.14	0.06	-0.19	-0.13
		Starch	-0.22	-0.22	0.01	0.17	0.18	0.09	0.14	0.04	0.11	0.14	0.00	-0.19	0.17	0.01	-0.02	0.03
	2004	Oil	-0.42	-0.44	0.20	0.36	0.64	0.59	0.56	0.24	0.21	0.28	0.05	-0.61	-0.07	-0.13	0.21	-0.06
		Protein	-0.60	-0.61	0.04	0.42	0.75	0.65	0.47	0.41	0.00	0.10	-0.07	-0.68	-0.07	-0.13	0.21	-0.02
		Starch	0.43	0.45	-0.21	-0.43	-0.66	-0.64	-0.50	-0.34	-0.12	-0.22	0.00	0.61	0.06	0.14	-0.21	0.02
	2006	Oil	-0.05	-0.06	-0.05	0.01	-0.03	-0.11	-0.07	0.00	-0.04	-0.04	0.06	0.07	0.00	0.06	-0.07	0.04
		Protein	-0.15	-0.11	0.14	0.05	0.02	0.10	0.11	0.20	0.09	0.12	0.10	-0.01	-0.07	0.03	0.00	-0.04
		Starch	0.26	0.24	0.11	0.02	-0.08	-0.10	-0.08	-0.15	-0.07	-0.08	-0.08	0.06	0.13	-0.09	0.02	0.16
WB	2002	Oil	-0.44	-0.41	0.10	0.29	0.58	0.52	0.18	-0.06	0.14	0.27	-0.58	-0.58	-0.49	-0.09	0.23	-0.10
		Protein	0.29	0.25	-0.06	-0.12	-0.34	-0.31	-0.11	-0.11	-0.27	-0.28	0.38	0.33	0.41	0.03	-0.26	0.08
		Starch	0.43	0.38	-0.10	-0.20	-0.55	-0.55	-0.22	0.08	-0.15	-0.33	0.50	0.50	0.47	0.09	-0.18	0.10
	2004	Oil	-0.06	-0.12	0.14	0.20	0.19	0.18	0.01	-0.03	0.27	0.19	-0.08	-0.14	-0.11	-0.10	-0.01	-0.25
		Protein	-0.16	-0.11	0.06	0.07	-0.02	0.07	0.14	-0.03	0.13	0.07	0.04	-0.02	-0.09	-0.05	-0.03	-0.11
		Starch	0.22	0.21	-0.19	-0.11	-0.10	-0.13	-0.03	-0.04	-0.12	-0.10	0.03	0.13	0.13	0.11	0.01	0.13
	2006	Oil	-0.14	-0.21	-0.13	0.04	0.14	0.07	0.02	0.00	-0.10	-0.09	0.00	-0.06	0.05	-0.03	-0.02	-0.05
		Protein	-0.41	-0.39	-0.06	0.02	0.12	0.09	0.00	0.02	-0.15	-0.14	0.00	-0.12	0.03	-0.14	0.02	-0.06
		Starch	0.43	0.47	0.19	-0.05	-0.19	-0.10	-0.03	0.02	0.15	0.16	0.11	0.20	-0.02	0.12	-0.03	-0.03

†Correlations differ from zero ($p \leq 0.05$) if $\rho > 0.10$ for site AN in 2006, and if $\rho > 0.12$ for all other site-years.

‡Organic Matter

§Total Organic Carbon

¶Total Nitrogen

#Phosphate-Borate Mineralizable Nitrogen

Table 5-6. Correlation coefficients for corn quality parameters within sites and across years.†

		— Protein —		— Oil —		—Starch—	
Site	Year	2002	2004	2002	2004	2002	2004
AN	2004	-0.19		-0.36		0.20	
	2006	-0.13	0.29	0.06	0.01	0.08	0.48
WB	2004	0.41		0.01		0.06	
	2006	0.52	0.28	0.18	0.08	0.03	-0.03

†Correlations differ from zero ($p \leq 0.05$) if $\rho > 0.08$.

Table 5-7. Correlation coefficients between corn quality parameters and yield by site-year and by N treatment.†

			All N rates			0 kg ha^{-1} N rate			N rates > 120 kg ha^{-1}		
Site	Year	Variable	Oil	Protein	Starch	Oil	Protein	Starch	Oil	Protein	Starch
AN	2002	Protein	0.01			0.13			-0.21		
		Starch	-0.79	-0.51		-0.84	-0.58		-0.86	-0.15	
		Yield	-0.03	0.59	-0.24	-0.21	0.28	0.02	-0.06	0.16	0.01
	2004	Protein	0.67			0.90			0.69		
		Starch	-0.79	-0.79		-0.93	-0.91		-0.78	-0.81	
		Yield	0.09	0.43	-0.21	0.54	0.72	-0.57	0.05	0.48	-0.20
	2006	Protein	0.05			-0.06			0.19		
		Starch	-0.22	-0.86		-0.28	-0.73		-0.39	-0.62	
		Yield	-0.02	0.74	-0.56	-0.21	0.87	-0.49	-0.04	-0.21	0.31
WB	2002	Protein	-0.56			-0.35			-0.69		
		Starch	-0.81	0.24		-0.78	0.08		-0.85	0.47	
		Yield	-0.43	0.42	0.30	-0.38	0.57	0.10	-0.49	0.48	0.43
	2004	Protein	0.37			0.73			0.24		
		Starch	-0.37	-0.67		-0.66	-0.76		-0.35	-0.60	
		Yield	-0.08	0.26	-0.05	-0.11	0.20	-0.05	-0.12	0.17	0.15
	2006	Protein	0.45			0.58			0.41		
		Starch	-0.50	-0.75		-0.56	-0.77		-0.49	-0.69	
		Yield	0.40	0.63	-0.40	0.37	0.55	-0.33	0.41	0.64	-0.40

†Correlations differ from zero ($p \leq 0.05$) if $\rho > 0.08$ for correlations including data from all N rates, if $\rho > 0.24$ for correlations including data from 0 N rates only, and if $\rho > 0.12$ for correlations including data from N rates > 120 kg ha^{-1}.

CHAPTER 6: Corn Yield Response to N and P in Relation to Soil Variability[1]

ABSTRACT

Corn [*Zea mays* L.] is often highly responsive to N fertilizer, but the controls over the magnitude of corn N response are largely unknown. Our objectives were to determine whole-field and site-specific economic optimum N rates (EONR) for two south-central Minnesota fields over six years of a corn-soybean [*Glycine max* (L.) Merr.] rotation, and to determine the relationships between EONR, P fertilizer treatments, and soil chemical and topographical variables. Corn yields responded significantly to N rate and N rate x P rate interaction in all site-years. Response to P was greatest in the cool and wet 2004 growing season. Whole-field EONR differed significantly by site-year and by P treatment at some site-years.

INTRODUCTION

Nitrogen is the single-most limiting nutrient to terrestrial plant productivity (Vitousek and Howarth, 1991), and the significance of N to crop productivity has long been recognized (Lawes et al., 1882). Like other grain crops, corn is often highly responsive to fertilizer N, and in many situations the most profitable yield cannot be obtained without N fertilizer application (Rehm et al., 2006). However, fertilizer N is a relatively expensive agronomic input, and currently amounts to the second-largest variable expense for corn production after land cost (Brudelie and Deters, 2010; Duffy, 2011). Application of N in excess of crop requirement results in economic losses to the producer (Sawyer et al., 2006). In addition, N losses to the environment increase when available N exceeds crop requirement (Dobermann et al., 2006; Randall and Mulla, 2001;

[1] P. Anthony, G. Malzer, S. Sparrow, and M. Zhang. Prepared as an article for Agronomy Journal.

Schlegel et al., 1996; Sexton et al., 1996). For both economic and environmental reasons, corn producers have an interest in applying optimum N rates.

Over the past several decades, considerable resources have been invested in efforts to identify optimum N rates for corn. Most of this research has been conducted by replicating large numbers of small-plot N fertilizer trials over many sites and many years, modeling yield response to N, and determining mean N rates at which economic return to N is maximized. Results are often reported as an economic optimum nitrogen rate (EONR) (Hanway and Dumneil, 1955) or as a rate of maximum return to nitrogen (MRTN) (Nafziger et al, 2004). Results are often categorized by previous crop or by soil productivity (e.g. Rehm et al., 2006), but are intended to serve as guidance for producers that is applicable across whole fields, farms, states, and regions (Sawyer et al., 2006).

Agricultural researchers have long understood the inherent variability in crop production within agricultural fields (Mercer and Hall, 1911). Over the past two decades, development of precision agriculture technologies that allow variable rates of fertilizer N has led to research emphasis on spatial variability in N response. This research has indicated that EONR for corn varies spatially within fields (Malzer et al., 1996; Scharf et al., 2005), and that the spatial pattern of EONR may vary across years in a given field (Lambert et al., 2006; Mamo et al., 2003). Since producers typically apply uniform N rates across whole fields, the rate of N applied is frequently different from the EONR (Scharf et al., 2005).

In order to understand the controls over EONR across space and time, site-specific EONR must be related to other site-specific parameters. To determine such relationships, researchers have suggested both corrective, implicit approaches, and also predictive, explicit approaches (Dobermann and Cassman, 2002; Schmidt et al., 2010). Predictive, explicit approaches use N response trials to determine site characteristics that relate to EONR, and then use site information and observed relationships to predict EONR at new sites (Kyveryga et al., 2011). Corrective, implicit approaches are based on in-season sensing of crop N sufficiency and ensuing application of fertilizer N to correct observed deficiencies (Scharf and Lory, 2009). While this approach eliminates temporal uncertainties associated with predictive, explicit approaches, previous research in the Northern Corn Belt indicates that N deficiencies may not become apparent in a corn-soybean rotation until the crop has entered a stage of rapid and critical N uptake and is too large for application equipment to enter (Miao et al., 2009). The limited research available on predictive, explicit estimation of corn N requirement has reported relationships between EONR and soil N mineralization (Ruffo et al., 2006) and soil moisture availability (Schmidt et al., 2010). In some cases, relationships between EONR and terrain attributes have been used as a surrogate for moisture measurements (Jaynes et al., 2011).

The uncertainty associated with whole-field estimates of EONR is often large, and confidence intervals are frequently >25% of EONR (Hernandez and Mulla, 2008; Jaynes, 2011). Although research has often indicated a wide range of variation in site-specific EONR, reports of the errors associated with site-specific EONR estimates are limited. Jaynes et al. (2011) reported confidence intervals for management-zone based EONR, but site-specific EONR error estimates have not been reported in approaches that have estimated EONR for small, regularly gridded divisions of fields. Both spatial econometric and geostatistical approaches have been used to estimate site-specific EONR for small and regular divisions of whole fields. Comprehensive reviews of these methods have been written by Bullock and Lowenburg-DeBoer (2007) and Oishi et al. (2006). However, there is little information available on the accuracy and precision with which these methodologies can predict true site-specific EONR. Estimating errors for site-specific EONR is difficult, as it must account for both the error in the spatial model used to predict yields at each location given the experimental design and also the error of the crop response model. However, without such error estimates it is not possible to evaluate the extent of significant differences in EONR across fields.

If corn producers are to realize potential benefits of precision N management, science must deliver understanding of the relationships and mechanisms that control N response in corn and must also provide clear assessment of the accuracy and precision of methodologies used to estimate site-specific EONR. With these goals in mind, we designed our research with the following objectives: (i) estimate whole-field and site-specific EONR for corn at two fields over six years of a corn-soybean rotation (ii) determine relationships between EONR, fertilizer P treatments, and a set of 16 soil chemical and topographical variables (iii) assess the accuracy and precision with which our experimental and analytical methodology could estimate true EONR.

MATERIALS AND METHODS

Site Description

Field experiments were established in the fall of 2001 on two 16-ha fields in south-central Minnesota. The two fields are located in Nicollet County (AN site, 44°23'N, 94°08'W) and Brown County (WB site, 44°08'N, 94°41'W). The sites were initially developed for agriculture in the 1860s, and have been in a corn–soybean rotation since the 1960s. We chose sites without a history of manure application within the past 5 years in order to minimize effects of mineralization of residual manure on the soil nutrient and mineralization tests. The soils at the AN site lie within a Clarion–Canisteo–Webster association, and consist of the of Canisteo series (fine-loamy, mixed, superactive, calcerous, mesic Typic Endoaquolls), Harps series (fine-loamy, mixed, superactive, mesic Typic Calciaquolls), Le Sueur series (fine-loamy, mixed, superactive, mesic Aquic Argiudolls), Cordova series (fine-loamy, mixed, superactive, mesic Typic Argiudolls), Okoboji series (fine, smectitic, mesic Cumulic Vertic Endoaquolls), and Lester series (fine-loamy, mixed, superactive, mesic Mollic Hapludalfs) (Jackson, 1994; USDA-NRCS, 2011). The soils at the WB site lie within a Nicollet–Clarion–Webster association, and consist of the Canisteo series, Clarion series (fine-loamy, mixed, superactive, mesic Typic Hapludolls), Nicollet series (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Okoboji series, and the Fieldon-Canisteo complex (fine-loamy to coarse-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) (Christensen, 1988; USDA-NRCS, 2011). Soils at both sites formed from calcareous glacial till. The

AN site is systematically tile drained on 30-m spacings; the WB site has limited tile drainage. Field management is typical for a corn-soybean rotation in south-central Minnesota and consisted of single-pass fall chisel-plowing or disking of soybean stubble and single-pass spring field cultivation prior to corn planting. Following corn harvest, disk-chisel tillage was used to incorporate corn residue. In each corn year, the farmer planted a single, commercial corn hybrid following typical production practices (Table 6-1). Temperature and precipitation data for the length of the experiment was obtained from the National Climatic Data Center (NCDC, 2011). Soil moisture data and solar radiation data was obtained from the University of Minnesota Climatology Working Group (CWG, 2009).

Experimental Design

The fertility experiment included 3 replications of 9 treatments in a split-plot arrangement of a randomized complete-block design. P (0 and 56 kg P ha^{-1}) was the main plot; N treatments (0, 50, 101, 152, and 202 kg N ha^{-1}) were applied in strips across the field, and placement of these strips was randomized within the P treatments. Because diammonium phosphate (DAP) was used as the P source, there was no 0 N ha^{-1} treatment within those plots where P was applied. The DAP rate provided N at a rate of 50 kg ha^{-1}. One extra 101 kg N ha^{-1} nitrogen strip was included in each block to avoid having 0 N ha^{-1} treatments repeated on the same strip in consecutive rotations; instead, the 0 N ha^{-1} treatments were applied to a strip that had received a 101 kg N ha^{-1} rate in the previous N application. All other treatments were applied to the same strip in each year of application. Identical design was applied at both sites. To ensure sufficient levels of soil K, K was applied to the entire field at a rate of 93 kg K ha^{-1}. All fertilizers were applied prior to the corn year of the corn-soybean rotation. N was applied as anhydrous ammonia with the nitrification inhibitor nitrapyrin (Dow AgroSciences, Indianapolis, IN, USA), P was applied as DAP, and K was applied as muriate of potash (KCl) in November 2001 and in November 2003 at both sites, and at site WB in November 2005. In April 2006, N was applied as anhydrous ammonia without nitrapyrin, P was applied as DAP, and K was applied as muriate of potash at site AN.

Grain Yield Measurements

In the falls of 2002, 2004, and 2006, plots were harvested with a modified Model 8 Massey Ferguson plot combine (AGCO Corp., Duluth, GA). This combine was equipped with an electronic ground distance monitor and a computerized HarvestMaster weigh cell (HarvestMaster, Logan, UT). Harvest measurements were taken from 15-m subplots along selected 9-m wide transects in each field. These 15-m sections corresponded to the 0.014-ha soil sampling grid cells. Transects were selected to obtain data from all combinations of N and P rates. The combine harvested two rows from the center of each selected transect. After each 15-m of travel distance, the harvested grain was weighed and a sample was taken for moisture analysis. In 2004 at site AN, 9 extra replicate strips were harvested; small areas of the experiment were not harvestable at site AN in 2002 and site WB in 2006. At site AN, 574, 792, and 594 individual subplots were harvested in 2002, 2004, and 2006, respectively; at site WB, 621 subplots were harvested in 2002 and 2004 and 614 subplots were harvested in 2006. Yield is reported as kg ha^{-1} on a 15.5% moisture basis.

Soil Chemical and Topographical Variables

The soil sampling and analysis protocol is described in detail by Anthony et al. (2012). Briefly, soils were sampled in the fall of each year 2001–2007. Samples were taken from 9 m x 15 m (0.014 ha) grid cells along a subset of the 36 transects of the N plots. In the falls of 2001–2004, 6 transects were sampled, totaling 132 samples per year at site AW and 138 samples per year at site WB. In the falls 2005–2007, 12 transects were sampled, totaling 264 samples per year at site AN and 276 samples per year at site WB. In the fall of 2001, 0- to 15-cm samples from each cell were analyzed for Bray P, Olsen P, K, pH, organic matter, and Zn; 0- to 60-cm samples from each cell were analyzed for total organic C, total Kjeldahl N, NH_4–N, NO_3–N, and mineralizable N. To determine mineralizable N, we used the phosphate borate mineralizable N (PBMN) test described by Gianello and Bremner (1988) as modified by Clay and Malzer (1993). In all falls following, 0- to 15-cm samples were analyzed for Bray P1, Olsen P, K, and pH. In odd-numbered falls following, which were subsequent to the soybean harvest and preceding the corn year in the rotation, 0- to 60-cm samples were taken and analyzed for NH_4^+–N, NO_3^-–N, and mineralizable N. Soil test values for grid cells which were not sampled in a particular year were estimated using cokriging in the Spatial Analyst extension of Arc View 9.3 (Environmental Systems Research Inst., Redlands, CA, USA). Soil test values for each 0.014-ha grid cell were extracted as the cell mean from kriged rasters and used for further analysis.

Elevation and position measurements were made on each field using survey grid GPS (horizontal accuracy +/- 0.5 m) and land-based laser (vertical accuracy +/- 0.05 m). Elevation measurements were made on a semi-regular grid with mean distance between points of approximately 20 m. These coordinates were used to create a digital elevation model of the fields using kriging in the Spatial Analyst extension of ArcView 9.3. The DEM raster was used to generate slope, curvature, and aspect rasters using these respective tools in the ArcView Spatial Analyst. The Fill, Flow Direction, and Flow Accumulation tools of the Arc View 9.3 Spatial Analyst extension were used to derive a hydrologic flow accumulation raster for each field. Mean values of the elevation, slope, curvature, aspect, and flow accumulation for each 0.014-ha grid cell of the field were extracted and used in further analysis.

Statistical Analysis

To determine significance of N and P treatment effects, we conducted a split-plot analysis of variance using the *aov* function in R version 2.12.1 (R Development Core Team, 2010). To maintain a balanced design, analysis was conducted only on N rates that were in common between P treatments, which excluded the 0 N rate in this analysis. At site AN in 2006, N treatments were ordered 0 through 4 in order to accommodate analysis of variance in light of the N application error.

As yields within treatment levels were not always normally distributed and samples sizes varied, simultaneous inference between all levels of N and P treatment combinations within site-years was determined using the Kruskal-Wallis non-parametric multiple comparison test (Conover, 1999). The Kruskal-Wallis test was conducted using the *kruskal* function of the *agricolae* package (de Mendiburu, 2010) for R version 2.12.1 (R Development Core Team, 2010).

Economic optimum N rates for each P treatment within each site-year were determined using both quadratic-plateau and quadratic models. Economic optimum N rates were calculated based on an N price ($\$\ kg^{-1}$) to corn price ($\$\ kg^{-1}$) ratio of 5.6, which is the average ratio over the crop years 2005–2010 in the US Midwest (Erickson et al., 2009). Akaike information criterion (AIC) was calculated to support model selection. Confidence intervals for calculated EONRs were determined at the 68% significance level using the method described by Hernandez and Mulla (2008), using the *confint* function of the *MASS* package (Venables and Ripley, 2002) in R. Significant differences between calculated EONRs were determined by assessing overlap of the 68% confidence bands (Jaynes et al., 2011; Schenker and Gentleman, 2001).

We used geostatistics to analyze the spatial structure of variability in corn yield. When necessary, data was log-transformed in order to normalize the distributions and most closely meet the assumption of intrinsic stationarity. Sample variograms were calculated and were fitted with exponential, spherical or gaussian models using weighted least-squares regression; models were selected to minimize the Akaike information criterion (AIC). Values were estimated for the variogram range, sill, and nugget. The proportion of variance in the data attributable to spatial correlation was characterized by the ratio of structural variance (sill-nugget) to the sill. Geostatistical analysis was conducted using the *geoR* package (Ribeiro and Diggle, 2001) for R version 2.12.1 (R Development Core Team, 2010). Temporal stability of corn quality was determined using the ranked correlation technique described by Lamb and Rehm (2002), in which correlations are determined between variables at ordered locations. To evaluate relationships between soil variability and corn yield, we calculated correlation coefficients between yield and each soil variable for all site-years. In order to avoid confounding effects of fertilizer treatments, we calculated these correlations using only a subset of the data in which N rates were greater than 120 kg ha^{-1}, which represents typical production practices in south-central Minnesota. Correlations were determined using the *cor* function in R version 2.12.1 (R Development Core Team, 2010).

RESULTS AND DISCUSSION

Weather Variation

Growing season conditions in southern Minnesota were warm and dry in 2002. Growing-degree units were above normal, but solar radiation was below normal. A cool May was followed by much above normal temperatures in June and July, with 11 days exceeding 32 C in these two months. August temperatures were near normal, and September temperatures were above normal. Growing season precipitation was below normal. July was particularly dry, and soil moisture on 1 August was considerably below normal. This year was particularly dry at site WB. The 2004 growing season was persistently cool and damp, with below normal growing degree units and below normal solar radiation. Temperatures in the months of May through August were slightly below normal, but were followed by a warm September. April precipitation was below normal, but the months of May through July had much above normal precipitation, and soils were approaching 100% of water-holding capacity on 1 August. This year was particularly wet at site AN. The 2006 growing season had above normal growing degree units and normal solar radiation. Temperatures were above normal from April through August, with a particularly large departure from normal temperatures in July. September was cool. Growing season precipitation was very close to the long-term mean, and large departures from normal precipitation were not observed in any month. Soil moisture on 1 August was above normal.

Fertilizer N and P Effects on Whole-field Mean Yields

Corn yield responses were significantly affected by N rate and N rate x P rate interaction in all years, and effects differed significantly by site-year (Table 6-2). For all site-years, highest yields were observed in the treatment combining the highest N rate and the highest P rate. For 5 of 6 site-years, lowest yields were observed in the treatment combining the 0 N and 0 P rates. At site WB in 2006, lowest yields were observed in the treatment combining 50 kg N ha^{-1} and 56 kg P ha^{-1}. Across all site-years, variability in yield tended to be reduced with increasing N rates, and in 19 of 24 cases, variability in yield was lower for a given N rate when P was also applied (Table 6-2). All 5 exceptions occurred in 2006. Lowest mean yields were observed at both sites in the warm and dry growing season of 2002, and corn yield was also least responsive to fertilizer treatments in this year (Table 6-2, Fig. 6-1). Corn yields responded most positively to application of fertilizer P in 2004 (Table 6-2, Fig. 6-1), when the growing season was particularly cool and wet weather, resulting in very slow plant development. Cold soil temperatures are associated with reduced P uptake by corn plants (Mackay and Barber, 1984), accounting for the strong positive response to fertilizer P in this year. Other soil fertility research in south-central Minnesota in the 2004 growing season has reported that corn in this region responded particularly strongly to fertilizer P in this year (Randall and Vetch, 2004).

The spatial patterns of corn yields differed significantly across years at both sites (Table 6-3). Differences were more pronounced for the 0 kg N ha^{-1} treatments than for the high N rate treatments (Table 6-3). At site AN, the spatial pattern of yields in years 2004 and 2006 were similar, especially for the 0 kg N ha^{-1} treatment. The spatial pattern of yields in the 2002 0 kg N ha^{-1} treatment was negatively correlated with the yield patterns in other years at this site. At site WB, we observed no correlations between in the spatial pattern of yields for the 0 kg N ha^{-1} treatment. In the high N rate treatments, positive correlations existed between years 2002 and 2004, and between 2004 and 2006. Previous research has reported similar temporal variation in the patterns of corn yields within fields (Lamb et al., 1997).

Relationships Between Soil Variables and Corn Yield

Correlations between soil variables and corn yield varied between sites, across years, and across N rates (Table 6-4). Positive correlations between yield and soil test P were strongest in 2004 at both sites. At site AN, this correlation was relatively weak in the 0 N treatments, but was strong in the high N rate treatments. At site WB, the positive correlation between yield and soil test P was equally strong in both the 0 N and high N treatments. These results agree strong positive response of corn yield to fertilizer P that we observed in this year (Table 6-2, Fig. 6-1). In 2006, we observed a negative correlation between yield and soil test P in the 0 N treatments at both sites. This result suggests that the negative response of yield to fertilizer P that we observed in the lowest N treatment at site WB in this year was part of a broader pattern of negative response of corn yield to P availability under low N supply. Corn yield was positively related to soil test Zn levels at all site-years except site WB in 2006. Corn yield was most positively related to soil test K in 2002, a drought-stressed year at both sites. Sufficient K supply is known to reduce the drought sensitivity of plants (Marschner, 1995). Correlations between yield and soil pH were more erratic, but tended to be most negative in 2004. The previously observed sensitivity of corn to P deficiency in this year was probably exacerbated in high pH soils. At site AN, yield in the 0 N treatments was strongly correlated with soil organic matter and total organic carbon in 2004 and 2006. This relationship may be related to the high intercorrelation between these variables and soil NO_3–N in these site-years. Yield in the 0 N treatments at site AN in 2004 and 2006 was highly correlated with both soil NO_3–N, total Kjeldahl N, and PBMN, but at site WB these correlations were significant only in 2004. The lack of consistent relationship between measures of soil available N and yield at site WB may be related to very poor soil drainage at this site. The resulting wide variation in soil saturation at this site could have allowed spatial variability in denitrification, leaching, or water-induced limits on N mineralization to dominate the relationship between N and crop yield at this site. In the relatively wet year of 2004, positive correlation was observed between yield and elevation when fertilizer N was sufficient. Apart from this relationship, we observed no consistent relationships between topography and yield.

Whole-field mean Economic Optimum Nitrogen Rates

Whole-field mean EONR differed significantly by site-year, by P application, and by the model chosen to fit EONR (Table 6-5, Fig. 6-2). In all cases, the quadratic response model indicated a numerically higher EONR than the quadratic-plateau model. The tendency for quadratic response models to indicate higher EONRs has been previously reported (Bullock and Bullock, 1994; Cerrato and Blackmer, 1990). However, the EONR indicated by the quadratic response model was significantly greater than that indicated by the quadratic-plateau model in only 7 of 12 cases. Akaike Information Criterion values indicated that the quadratic response model was most appropriate in 3 of 12 cases, while the quadratic-plateau model was most appropriate in 7 of 12 cases. In two cases both models had identical AIC values. All 3 cases in which the quadratic response model provided the best fit were in plots receiving 0 kg P ha^{-1}. In the 0 P treatments, yields often tended to decline when the N rate increased from 151 kg N ha^{-1} to 202 kg N ha^{-1} (Table 6-2, Fig. 6-1), and the quadratic response model was better able to fit this decline in yield at the highest N rate. The best-fitting model for each combination of P rate and site-year as indicated in Table 6-5 and Fig. 6-2 will be used in discussion from this point forward. In all cases, the quadratic model resulted in narrower confidence bands for the EONR than the quadratic-plateau model. This tendency for the quadratic model to produce narrower confidence bands has also been observed by Jaynes (2011).

In the 0 P treatments at site AN, whole-field mean EONR was not significantly different across years. At site AN in 2002, whole-field mean EONR was not significantly different between P rates; however, whole-field EONR was significantly higher in the 56 kg P ha^{-1} treatments compared with the 0 kg P ha^{-1} treatments at this site in 2004 and in 2006. When P was applied, 63 and 39 kg ha^{-1} more N was required to optimize corn yield at site AN in these two years, respectively. In the 0 P treatments at site WB, whole-field mean EONR was not significantly different between 2002 and 2004, but was significantly higher in 2006 than in 2002–2004. Where P was applied, EONR was significantly higher than the 0 P treatment in 2002, but not in 2004–2006. Synergistic interaction effects of N and P have been widely reported in corn (Aulakh and Malhi, 2004), but we are not aware of previous reports of significantly higher whole-field EONR associated with P applications.

Within years, EONR difference between sites varied by year. In 2002, EONR in the 0 P treatment was slightly higher at site AN, but EONR in the 56 kg P ha^{-1} treatment was not significantly different between sites. In 2004, EONR at site WB was significantly lower than at site AN in both of the P treatments. In 2006, EONR in the 0 P treatment was significantly higher at site WB, but EONR in the 56 kg P ha^{-1} treatment was not significantly different between sites.

Whole-field EONR was within the range of current University of Minnesota Extension Service recommendations for corn following soybeans (100–140 kg N ha^{-1}) at the N price to corn price ratio used in our calculations in 8 of 12 cases (Rehm et al., 2006). In 4 of 12 cases, whole-field EONR was 30-50% higher than current recommendations. These 4 cases occurred in the 56 kg P ha^{-1} treatments at site AN in 2004 and 2006, and in both P treatments at site WB in 2006. Recent research has indicated potential for substantial losses of N from fall-applied ammonium phosphate fertilizers. In this experiment, we credited 100% of ammonium phosphate-N to the total N rate. It is possible that N losses from the ammonium phosphate source (Fernandez et al. 2010) could account for higher EONR in the 56 kg N ha^{-1} P treatments. However, at site AN in 2004, the site-year in which the EONR difference was greatest between the P and 0 P treatments, yields were not statistically different between P and 0 P treatments at the 50 kg ha^{-1} level of N. If substantial quantities of N had been lost, we would have expected a lower yield in the P treatment due to N limitation. While this direct comparison was not available at site AN in 2006, a decrease in yield at low N rates in the P treatments could also be attributed to the negative correlation between yield and soil test P that we observed in the 0 N treatments at both sites in 2006.

SUMMARY AND CONCLUSIONS

Corn yield was greatly influenced by N rate and N rate by P rate interaction in this 6-yr experiment. For all six site-years, highest yields were observed in treatments combining the highest N and P rates. In 4 of our 12 trials, EONR was significantly higher than current University Extension Service N rate recommendations, with EONR exceeding current recommendations by 30–50%. In 3 of 6 site-years, a 56 kg ha^{-1} P application was associated with significant increases in EONR. Current N rate recommendations do not account for synergistic interactions between crop nutrients. In our experiment, we observed synergistic effects of N and P fertility on both corn yield and on EONR.

Corn yield was positively correlated with soil test Zn levels. Other correlations were year-dependent. Correlations between yield and STP were strongest in 2004, when conditions were cool and wet. Correlations between yield and soil test K were strongest in 2002, a droughty year.

In summary, these results suggest that farmers and agronomists should consider potential effects of synergistic interactions of N rate and P fertility when making N rate decisions.

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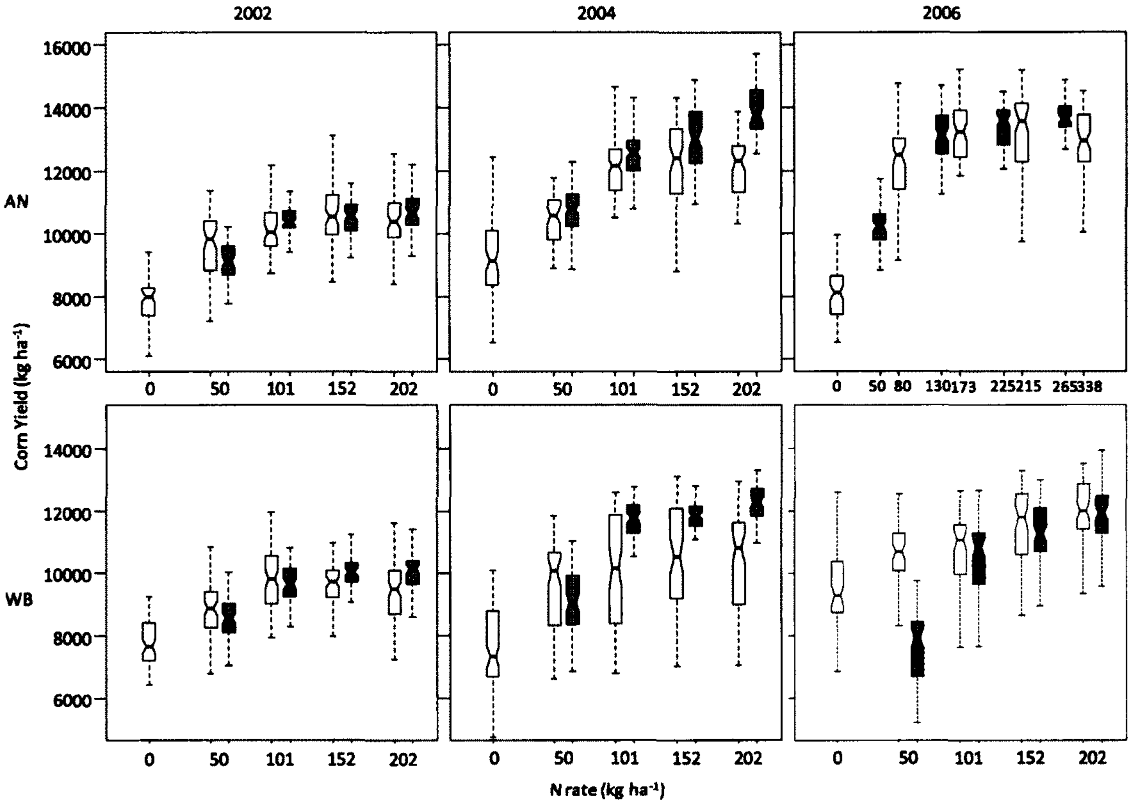

Fig. 6-1. Corn yield response to N and P treatments by site-year. White boxes represent 0 P kg^{-1} treatments; grey boxes represent 56 kg P ha^{-1} treatments. Black lines indicate median values, boundaries of the boxes indicate first and third quartiles, and whiskers extend to up to 1.5 times the interquartile range.

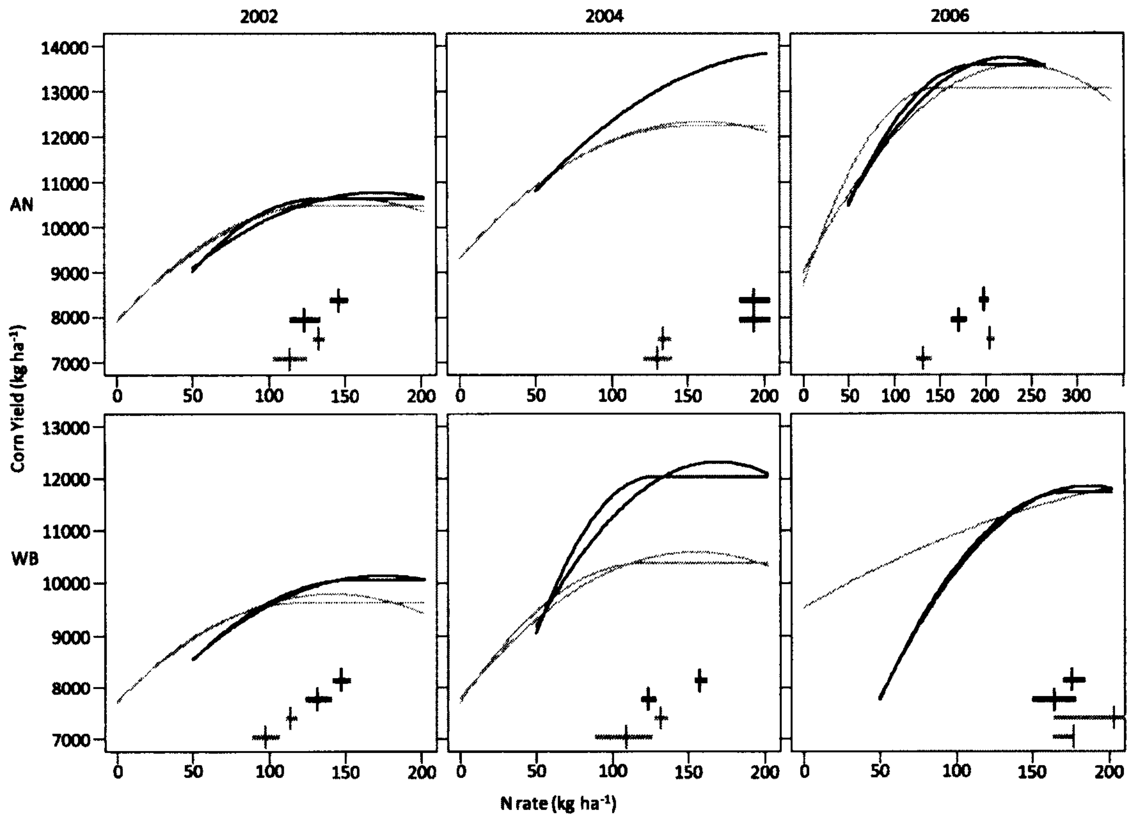

Fig. 6-2. Fitted whole-field curves of corn yield response to N by site-year. The top row of panels presents data for site AN; the bottom row for site WB. Grey lines indicate quadratic and quadratic-plateau response curves in 0 kg P ha^{-1} treatments; black lines indicate quadratic and quadratic-plateau response curves in 56 0 kg P ha^{-1} treatments. Boxplots below response curves indicate the estimate of economic optimum N rate (EONR) and 68% confidence bands for EONR. From bottom to top for each frame, boxplots show EONR for 0 kg P ha^{-1} quadratic, 0 kg P ha^{-1} quadratic-plateau, 56 kg P ha^{-1} quadratic, and 56 kg P ha^{-1} quadratic-plateau models. Overlap of confidence bands indicates no significant difference between estimated EONR.

Table 6-1. Summary of agronomic information by site-year.

Site	Year	Hybrid	Population	Row Width	Planting Date
			seeds ha^{-1}	cm	
AN	2002	Pioneer 35R57	80,000	56	18 April
	2004	Dekalb 51-43	81,000	56	24 April
	2006	Dekalb 52-47	80,000	56	17 April
WB	2002	Pioneer 34G82	79,000	76	24 April
	2004	Pioneer 36N71	79,000	76	24 April
	2006	Dekalb 51-39	79,000	76	24 April

Table 6-2. Summary statistics of corn yield response to N and P fertilizer treatments by site-year.

	Site AN						Site WB					
			Grain yield						Grain Yield			
Year	P rate	N rate	Mean	Maximum	Minimum	CV	P rate	N rate	Mean	Maximum	Minimum	CV
	kg ha^{-1}											
2002	0	0	7860 f†	9418	6114	8.3	0	0	7770 f	9249	6428	9.2
	0	50	9583 d	11377	7223	10.7	0	50	8829 d	10851	6817	8.6
	56	50	9066 e	10240	7250	7.2	56	50	8547 e	10034	7041	7.6
	0	101	10213 c	12252	7776	8.3	0	101	9848 b	11953	7968	9.3
	56	101	10399 b	11728	8779	5.8	56	101	9662 bc	10808	8301	6.1
	0	152	10613 ab	13805	8466	9.5	0	152	9611 be	10947	7995	7.9
	56	152	10530 ab	11601	9218	5.4	56	152	10030 a	11254	8774	4.9
	0	202	10382 bc	13184	8403	8.7	0	202	9465 c	11625	7255	10.5
	56	202	10727 a	12713	9281	6.1	56	202	10087 a	11723	8614	6.0
2004	0	0	9475 f	14125	6522	17.6	0	0	7693 f	10096	4711	16.8
	0	50	10417 ef	11761	8890	7.5	0	50	9566 d	11830	6608	14.9
	56	50	10734 e	12260	8874	6.5	56	50	9057 e	11025	6862	10.8
	0	101	12143 d	14649	10512	7.5	0	101	10147 c	12560	6801	17.7
	56	101	12543 b	14305	10797	6.0	56	101	11692 b	12774	8820	6.0
	0	152	12232 d	14322	8813	10.4	0	151	10490 c	13102	7017	15.3
	56	152	13017 b	14865	10923	7.5	56	151	11837 b	12781	10567	3.6
	0	202	12074 d	13888	10330	8.0	0	202	10398 c	12960	7055	15.6
	56	202	13953 a	15699	12537	5.7	56	202	12217 a	13279	10950	4.5
2006	0	0	8714 f	13967	6524	23.8	0	0	9423 d	12593	6871	15.5
	56	50	10468 f	13980	8828	10.4	0	50	10572 c	12527	7031	11.8
	0	82	12225 e	14741	9137	11.3	56	50	7744 e	9759	5169	13.7
	56	132	13055 cd	14682	11255	6.5	0	101	10728 c	12623	7480	11.7
	0	174	13244 bcd	15212	11822	6.5	56	101	10526 c	12632	6995	12.3
	0	215	13027 bc	15197	9142	12.2	0	152	11492 ab	13286	7051	11.7
	56	224	13416 b	14519	12059	4.8	56	152	11346 b	12991	8947	8.1
	56	265	13738 a	15275	12670	4.0	0	202	11829 a	13514	8109	10.9
	0	338	12927 d	14521	10027	7.1	56	202	11879 a	13939	9578	8.7

Analysis of Variance

Source of Variation	df	Pr>F
P rate	1	ns
N rate	3	***
P rate x N rate	3	***
Year x P rate	2	***
Site x P rate	1	ns
Year x N rate	6	***
Site x N rate	3	***
Year x Site x P rate	2	ns
Year x Site x N rate	6	***
Year x P rate x N rate	6	***
Site x P rate x N rate	3	***
Year x Site x P rate x N rate	6	**

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

†Within site-years, mean grain yields followed by the same letter are not significantly different according to the Kruskal-Wallis test ($P \leq 0.05$).

Table 6-3. Inter-year correlation coefficients between corn yields within sites for plots receiving 0 kg N ha^{-1} (left columns) and plots receiving ≥150 kg N ha^{-1} (right columns).†

		0 kg N ha^{-1}		≥150 kg N ha^{-1}	
Site	Year	2002	2004	2002	2004
AN	2004	-0.50		0.23	
	2006	-0.55	0.75	-0.07	0.41
WB	2004	0.24		0.55	
	2006	0.04	-0.17	0.05	0.36

†*For 0 kg N ha^{-1} rate, correlations differ from zero (P≤0.05) if ρ>0.10 for site AN in 2006, and if ρ>0.12* for all other site-years; for N rates ≥150 kg N ha-1, correlations differ from zero (P≤0.05) if ρ>0.24.

Table 6-4. Correlation coefficients between corn yield and soil chemical and topographical variables by site-year and by N rate.†

N Rate	Site	Year	Bray P	Olsen P	Zn	K	pH	OM	TOC	NH4	NO3	TN	PBMN	Elevation	Slope	Curvature	Flow	Aspect
0	AN	2002	0.07	0.07	0.42	0.35	-0.10	0.07	0.02	0.33	0.01	0.10	0.01	-0.13	0.00	-0.40	0.03	-0.15
0		2004	0.15	0.02	0.58	0.18	0.43	0.66	0.86	-0.47	0.87	0.86	0.76	-0.62	-0.20	0.03	0.22	0.18
0		2006	-0.35	-0.34	0.39	0.11	0.64	0.81	0.90	-0.08	0.89	0.84	0.64	-0.73	-0.37	-0.23	0.34	-0.10
0	WB	2002	0.08	0.01	0.09	0.15	-0.05	0.04	0.16	0.02	0.10	-0.05	0.10	-0.03	0.03	-0.14	-0.17	-0.10
0		2004	0.51	0.62	0.46	0.17	-0.55	-0.25	0.23	0.31	0.39	0.40	0.64	0.39	0.20	-0.11	0.15	0.15
0		2006	-0.39	-0.13	-0.34	-0.42	0.07	0.45	0.06	-0.40	0.18	0.03	-0.02	0.22	0.07	0.09	-0.22	-0.50
≥150	AN	2002	0.36	0.31	0.28	0.18	-0.32	-0.25	-0.29	-0.06	-0.13	-0.18	0.04	0.27	0.08	0.00	-0.10	0.15
≥150		2004	0.51	0.45	0.36	0.05	-0.37	-0.34	-0.14	-0.33	0.13	0.09	0.12	0.32	0.12	0.16	-0.08	0.16
≥150		2006	0.18	0.16	0.29	0.12	0.03	0.17	0.22	0.10	0.22	0.22	0.17	-0.12	-0.07	-0.26	0.11	0.02
≥150	WB	2002	0.32	0.29	0.16	0.21	-0.20	-0.19	-0.23	0.15	0.16	-0.24	0.19	0.16	0.17	-0.01	0.06	-0.05
≥150		2004	0.52	0.53	0.19	-0.13	-0.55	-0.46	-0.15	-0.07	-0.07	-0.05	0.48	0.47	0.31	0.10	-0.02	0.12
≥150		2006	-0.07	0.11	-0.25	-0.54	-0.40	-0.15	0.10	-0.19	0.28	0.23	0.32	0.41	0.41	-0.01	-0.31	-0.02

† For 0 kg N ha^{-1} rate, correlations differ from zero ($P \leq 0.05$) if $\rho > 0.10$ for site AN in 2006, and if $\rho > 0.12$ for all other site-years; for N rates ≥150 kg N ha-1, correlations differ from zero ($P \leq 0.05$) if $\rho > 0.24$.

Table 6-5. Akaike Information Criterion (AIC), Economic Optimum N Rate (EONR), confidence intervals for EONR at the 0.68 level, and predicted corn yield at EONR for quadratic plateau and quadratic yield response models by P treatment, year, and site.

Site	Year	P Treatment	Model	AIC	EONR	16%	84%	Range	Yield at EONR
		kg P ha^{-1}			———	kg N ha^{-1}	———		—kg ha^{-1}—
AN	2002	0	Quadratic Plateau	5106.91	114.0	102.9	123.2	20.3	10425
		0	Quadratic	5106.25	128.6	124.6	133.2	8.6	10568
		56	Quadratic Plateau	4152.96	120.3	112.9	127.4	14.5	10596
		56	Quadratic	4163.64	146.7	142.8	151.3	8.4	10697
	2004	0	Quadratic Plateau	6713.23	130.2	121.8	139.3	17.5	12171
		0	Quadratic	6711.00	135.4	130.5	141.1	10.7	12262
		56	Quadratic Plateau	6429.65	193.1	183.3	206.0	22.6	13789
		56	Quadratic	6429.65	193.1	183.4	206.0	22.6	13789
	2006	0	Quadratic Plateau	5740.17	132.6	121.7	143.8	22.1	13027
		0	Quadratic	5761.67	203.3	198.3	208.7	10.4	13470
		56	Quadratic Plateau	4292.39	171.6	163.3	179.9	16.5	13528
		56	Quadratic	4305.49	197.4	192.8	202.9	10.2	13664
WB	2002	0	Quadratic Plateau	5635.79	98.6	91.8	105.9	14.0	9562
		0	Quadratic	5632.93	113.9	110.6	117.4	6.7	9720
		56	Quadratic Plateau	4307.56	135.0	127.4	144.0	16.6	10004
		56	Quadratic	4308.99	146.7	143.0	151.3	8.3	10071
	2004	0	Quadratic Plateau	6055.55	106.2	86.9	123.8	36.9	10350
		0	Quadratic	6057.06	130.6	124.2	138.6	14.4	10525
		56	Quadratic Plateau	4411.21	121.2	116.1	126.2	10.2	12011
		56	Quadratic	4448.65	156.7	153.8	160.0	6.2	12279
	2006	0	Quadratic Plateau	5823.99	203.1	162.2	NE†	NE	11816
		0	Quadratic	5823.99	203.1	163.7	364.4	200.7	11816
		56	Quadratic Plateau	4652.78	162.5	149.7	174.4	24.7	11696
		56	Quadratic	4654.01	173.1	167.5	180.1	12.6	11813

†Not Estimable.

CHAPTER 7: Elemental Sulfur for Soil pH Reduction in Calcareous Mollisols of the North-Central United States[1]

ABSTRACT

High pH, calcareous soils are a common feature of the prairie pothole region of the North-Central United States. Plant nutrient availability and uptake is limited on these soils, substantially reducing productivity of corn [*Zea mays* L.] and soybean [*Glycine max* (L.) Merr.]. We initiated a long-term experiment to study the efficacy and economic viability of elemental S application for soil pH reduction and improved crop yield. Application of 1200 kg S^0 ha^{-1} to a high pH (7.8), calcareous (CCE 3.94%) soil in Nov. 2010 resulted in significant reduction in soil pH after 1 yr, reducing pH by approximately 0.25 units. We observed no significant treatment effect on soybean yield in the first season after S^0 application. Soil SO_4–S levels indicated that a relatively small percentage of S^0 had been oxidized after 1 yr, and further pH reduction is likely in the future in treated plots. Economic analysis indicated that with recent levels of crop prices, relatively minor improvements in crop yield are sufficient to make S^0 amendment profitable at the rate used in this experiment. Crop yields will be monitored in future years to determine long-term efficacy and economic viability of S^0 application for pH reduction in these soils.

Abbreviations: CCE, calcium carbonate equivalent; EC, electrical conductivity; IDC, iron deficiency chlorosis; TDS, total dissolved solids

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[1] P. Anthony, G. Malzer, M. Zhang, S. Sparrow, and D. Valentine. Prepared as an article for Agronomy Journal.

INTRODUCTION

High pH, calcareous soils are a common feature of the prairie pothole region of the North-Central United States (Fig. 7-1). This region, coextensive with the Des Moines lobe of the Wisconsin glaciations, is characterized by gently sloping swell and swale relief typical of young glacial plains. Soils in this region formed from calcareous glacial till. As integrated drainage networks had not yet developed in this landscape, wetlands, or potholes, formed in the kettle depressions of the glacial drift. Evaporative discharge of water from soils on the wetland edges led to deposition of carbonates at the depressional rims (Richardson et al., 1994; Fig. 7-2), creating soils with pH 7.5–8.0. As the pH of these soils is dominated by calcium and carbonates, the limited solubility of calcite ($CaCO_3$) creates a strong buffering effect, preventing the pH from rising higher than ≈8.4. Precipitated calcite produces a white sheen on the soil surface, easily visible when these soils are bare.

European settlement of the prairie pothole region began in the middle of the 19th century, and native grasses were plowed and converted to dryland crop production. Initially, well-drained soils were tilled while potholes remained in native vegetation, which could be used as pasture or hay for livestock. However, during the 20th century a number of factors led to extensive wetland drainage in the prairie pothole region. First, concerns over food supply, especially during the two world wars, drove federal government programs to increase arable acres for coarse grain production through wetland drainage. Second, local concerns over mosquito-borne infectious diseases, especially those affecting draft horses, created interest in reducing mosquito habitat. Third, farms grew more specialized, and mechanized crop farms no longer needed the pasture and hay that was typically grown in wet, low-lying soils. Continual bypassing of wetlands with farm machinery required extra resources, reducing the efficiency of field operations and resulting in higher production costs (Leitch, 1989). As open-ditch and tile drainage networks grew, arable land expanded to include the high pH, calcareous soils on depressional rims. High pH, calcareous soils pose a number of problems for crop production. The essential crop nutrients P, Fe, Mn, Cu, B, and Zn undergo chemical changes that render them increasingly unavailable to plants as soil pH rises above 7.0. High pH also reduces the electrochemical driving force for anion nutrient uptake (Rufty et al., 1982) and affects root growth (Marschner, 2011). Optimal pH for growth differs among field crops. Corn [*Zea mays* L.] and soybean [*Glycine max* (L.) Merr.] dominate the southern portion of the prairie pothole region, and the optimal pH for these crops is <6.5 (Brady and Weil, 2002). In consequence, farmers observe substantially reduced corn and soybean yields in these soils. In soybeans, yield-reducing effects of high pH and calcite levels have been observed on ≈25% of planted acres, with estimated mean yield reductions of 0.8 Mg ha^{-1} (12 bu A^{-1}) and maximum yield losses approaching complete crop failure (Hansen et al., 2003; Inskeep and Bloom, 1987). Significant yield losses in corn have been associated with these soil types (Kaspar et al., 2004).

Efforts to manage and mitigate corn and soybean yield losses associated with high pH, calcareous soils in the prairie pothole region have focused on management of pH-induced micronutrient deficiencies, particularly iron deficiency chlorosis (IDC) in soybean. In soybean, iron deficiency results in interveinal chlorosis in newly-emerged leaves due to insufficient iron for chlorophyll formation. Researchers have examined many IDC management options, including variety selection (Fairbanks et al., 1987), increased seeding rates (Goos and Johnson, 2001), seed treatments of chelated iron (Goos and Johnson, 2000; Karkosh et al., 1988), foliar sprays of chelated iron (Goos and Johnson, 2000; Randall, 1981), and soil nitrate reductions through interseeding with small grains (Bloom et al. 2011). In contrast to management of low pH soils, where lime application to raise pH is a primary soil management recommendation for crop production (Kaiser et al., 2011), soil amendments to lower soil pH are not generally considered as a potential management strategy in the prairie pothole region (Naeve, 2006) and may be actively discouraged for economic reasons (Franzen, 1999; Rehm, 2002).

Generally, there is widespread acceptance of using soil amendments to lower pH in both horticulture and agriculture (Brady and Weil, 2002; Gale et al., 2001). Most commonly, elemental sulfur is used for this purpose. When elemental S is added to soil, autotrophic bacteria facilitate oxidation of reduced sulfur to sulfuric acid, a strong acid which almost completely dissociates in water solution. Dissociation results in hydrogen ions and sulfate anions:

(1) $2\ S^0 + 3\ O_2 + 2\ H_2O \rightarrow 4\ H^+ + 2\ SO_4^-$

In calcitic soils, the sulfuric acid produced in equation (1) reacts with calcite:

(2) $H_2SO_4 + CaCO_3 \rightarrow CO_2(g) + H_2O + CaSO_4$

The CO_2 produced leaves the soil as gas, and the relatively soluble gypsum may be leached from the soil.

Rates of S^0 oxidation may differ substantially across agricultural soils, and are influenced by microbial populations, physical factors regulating microbial activity, and the surface area of the applied S^0 (Germida and Janzen, 1993; Solberg et al., 2005b). Oxidation rates are most rapid when soil moisture is near field capacity and soil temperatures are in the range of 30–40°C, suggesting that tillage practices that lead to increased soil temperatures can result in higher S^0 oxidation rates (Solberg et al., 2005a).

While application of S^0 for pH reduction has not been encouraged in the prairie pothole region, there is a dearth of regional field research on the use of this soil amendment. The single research report we identified found high rates of S^0 to be effective in lowering soil pH and increasing the availability of P, Fe, Mn, Zn, and Cu in agricultural soils of eastern South Dakota (Gerwing and Gelderman, 1996). However, soybean yield was not significantly increased. The authors attributed the lack of positive yield response to salt-induced crop injury. Heavy applications of S^0 resulted in substantial addition of sulfate anions to the soil, increasing the level of soluble salts, which are the sum of soluble ions. More recent work has associated high soluble salt concentration with increased risk of crop injury in high pH, calcareous soils (Hansen et al., 2003).

There are reasons to expect that more favorable results might be expected from sulfur amendments for pH reduction in other portions of the prairie pothole region. Mean annual rainfall increases substantially west-to-east across the prairie pothole region (Fig. 7-3). When precipitation exceeds evapotranspiration, excess soil water leaches through the soil profile, carrying with it soluble salts. As mean excess precipitation increases markedly as one moves eastward (Fig. 7-3), problems of soluble salts may be expected to decline along the same gradient, especially in fields with adequate internal drainage.

Economic considerations have also changed since recommendations against sulfur amendments have been made (Franzen, 1999). Prices for corn and soybeans have risen substantially (Fig. 7-4), and farmland prices have increased as well (Fig. 7-4). In consequence of higher crop prices and production costs, the economic losses attributable to high pH, calcareous soils have risen sharply (Table 7-1). In light of these changes, soil amendments for pH reduction should also be reevaluated in an economic context.

This research project had two objectives: 1) to determine the short and long-term effects of sulfur application on soil pH, on visual symptoms of crop injury, and on crop yield; 2)to evaluate potential and actual economic impact of amelioration of high pH, calcareous soil conditions for row-crop production in the prairie pothole region.

MATERIALS AND METHODS

Site Description

Our field experiment was established in the fall of 2010 on an agricultural field in south-central Minnesota (44°24'N, 94°12'W) (Fig. 7-5). The field was developed for agriculture in the 1860s and has been in a corn–soybean rotation since the 1960s. The soils lie within a Clarion–Canisteo–Webster association. Portions of the field have a history of pH-related crop injury, including visual symptoms and yield loss. For our research, we chose one of these areas, a 5-ha (12.5 A) portion of the field mapped as a Canisteo-Webster depressional complex (fine-loamy, mixed, superactive, calcerous, mesic Typic Endoaquolls; fine-loamy, mixed, superactive, mesic Typic Endoaquolls) (Jackson, 1994; USDA-NRCS, 2011). These soils formed from calcareous glacial till.

Experimental Design

In Nov. of 2010, replicated, 21-m (70 ft) wide plots of S^0 were applied in the selected study area using a replicated complete-block design (Fig. 7-5). These plots were oriented in the same direction as planting and harvesting operations on this field, and alternated with 21-m (70 ft) wide plots which received no S^0. Sulfur was applied as 1333 kg ha^{-1} (1190 lb A^{-1}) Tiger 90CR (Tiger-Sul Products, Calgary, Canada), providing 1200 kg ha^{-1} (1071 lb A^{-1}) of S^0. Following application, the product was incorporated into the soil with one pass of a combination disk-ripper, operating at 20-cm depth. The cooperating producer planted a soybean variety with average IDC resistance (Nutech 7226) on the entire field in 2011.

Soil Chemical Analysis

To establish baseline soil chemical data, soil samples were taken with an intensive grid-based sampling protocol in the summer of 2010. In the fall of 2011, soils were sampled along transects centered on each of the eight plots. On each transect, three soil samples were taken. Each of these samples consisted of five cores from 0- to 15-cm (0- to 6-in) depth, one taken from a central point, and four taken from points on a 2-m (6.56-ft) radius around the central point.

All soil samples were air-dried and passed through a 2-mm (0.08-in) sieve. Samples were extracted using Bray P, Olsen P, ammonium-acetate K, sulfate S, and DTPA Zn extractions as described in Brown (1998). Phosphorus was determined using colorimetric methods and sulfate S was determined using turbidity methods on a FIAlab 2500 autoanalyzer (FIAlab Instruments, Belleuve, WA). Potassium and Zn were determined using a Perkin Elmer 3310 Atomic Absorption Spectrometer (Perkin Elmer Corporation, Waltham, MA). Soil pH and organic matter (OM) were determined according to Brown (1998). For baseline soil samples, we also determined calcium carbonate equivalent (CCE) and soluble salts. Calcium carbonate equivalent was determined using hydrochloric acid treatment and manometric measurement of evolved CO_2 (USDA-SCS, 1984). Soluble salts were determined by measurement of electrical conductivity (EC) in a 1:1 (v/v) soil water mixture.

Yield Analysis

In the fall of 2011, the field was harvested with a commercial combine equipped with a mass-flow-sensing yield monitor (Ag Leader, Ames, IA) calibrated to ±1% error and linked to a differential global positioning system receiver (DGPS). The harvesting width was 10.7 m (35 ft). A single harvesting pass was made through the center of each plot to eliminate potential errors induced by edge effects. Recorded harvest data was imported into ArcGIS 9.3 (ESRI, Redlands, CA), where the data was analyzed for errors and cleaned with the method of Drummond and Sudduth (2005). After cleaning, we determined the mean crop yield in each plot.

Statistical Analysis

We produced summaries of the soil and yield data using the aggregate function in R (R Development Core Team, 2011). The aov function in R was used to compute F statistics and p values to identify treatment effects with significantly different means ($p<0.05$) after adjusting for location block effects.

RESULTS AND DISCUSSION

Mean initial CCE of samples from the experimental area was 3.94%. Based on an average soil bulk density of 1.3 Mg m^{-3} (2190 lb yd^{-3}), approximately 80,000 kg $CaCO_3$ ha^{-1} (71,400 lb A^{-1}) are present in the 0- to 15-cm (0- to 6-in) depth interval in the experimental area. Neutralization of all alkalinity associated with the $CaCO_3$ in this soil would require approximately 25,000 kg S^0 ha^{-1} (22,300 lb A^{-1}). However, calcite often occurs in soils in relatively large particle sizes that are essentially unreactive, reducing the quantity of elemental S required for soil pH reduction. Accounting for unreactive calcite, rule of thumb estimates call for 1000 kg (2205 lb) S^0 for each 1% CCE (Havlin et al., 1993). We therefore expect that our 1200 kg ha^{-1} (1071 lb A^{-1}) rate of S^0 would neutralize some, though not all, of the 0- to 15-cm (0- to 6-in) soil calcite in our treatment plots.

Application of S^0 resulted in a significant decrease in soil pH for soil samples taken one yr after application (Table 7-2), with a mean pH decline of 0.24 units in the 0- to 15-cm (0- to 6-in) sampling depth. Sulfate S levels in the soil also increased significantly, with a mean increase of 24 mg SO_4–S kg^{-1} (24 ppm) (Table 7-2). This increase in soil SO_4–S is equivalent to the oxidation of 16 kg S^0 ha^{-1} (35 lb A^{-1}). While rainfall and soil drainage was above normal in the spring following application of S^0, summer and fall rainfall were much below normal and little leaching occurred after 15 June 2011. We therefore expect that relatively little leaching of SO_4–S occurred from the treated plots prior to the fall 2011 sampling. The mean increase of 24 mg kg^{-1} (24 ppm) in soil SO_4–S should therefore approximately reflect the total oxidation of elemental S that had occurred as of fall 2011. If this is the case, then a substantial portion of the 1200 kg S ha^{-1} (1071 lb A^{-1}) remains to be oxidized, providing potential for additional pH reduction in the future.

Electrical conductivity of soil was also significantly higher in the plots treated with elemental S, with a mean increase of 0.35 mmhos cm^{-1}. Higher EC values are likely due in part to higher levels of soil SO_4^{-2} (Gerwing and Gelderman, 1996) and Ca^{+2} ions produced through the reaction of sulfuric acid on calcite as shown in equation (2). However, estimation of the increase total dissolved solids (TDS) based on increase in soil EC ($\Delta TDS = 640 \times \Delta EC$) place the increase in TDS at approximately 224 mg kg^{-1} (224 ppm), which is more than four times greater than the combined increase in soil SO_4^{-2} and Ca^{+2} ions. While the calculation of TDS based on EC is only an estimate, we expect that the reduction in soil pH may also have led to an increase in P, Fe, and Zn in the soil solution, elements which become insoluble at higher pH (Kovar and Claassen, 2005;

Marschner, 2011). Gerwing and Gelderman (1996) reported increases in the availability of these elements when high soil pH values were reduced through application of elemental S.

While soil pH levels were reduced, we observed no significant treatment effect on soybean seed yields in the fall following S^0 application (Table 7-2). Lack of treatment response may be attributed to insufficient reduction in soil pH, a soil pH reduction that occurred too late in the season to have an effect on the crop in the first year following treatment, or to a detrimental effect of an increase in salt concentrations in the treated areas (Hansen et al., 2003). We also observed no visual effects of treatments on the soybean canopy. Future effects on yield will be governed by the balance of beneficial impact of future S^0 oxidation on pH and detrimental impact of elevated soluble salt concentrations in the root zone.

The economic viability of amelioration of high-pH soils with elemental sulfur depends on crop prices, elemental sulfur price, and the effectiveness of S^0 for reducing crop yield losses. Based on crop prices from 2010 (Table 7-1) and current prices for elemental sulfur (\$221 Mg^{-1}; \$200 ton^{-1}), the rate of S^0 used in this study would be economically viable if the magnitude of pH-related yield loss was reduced by only 5–10% (Table 7-3). Alternatively, the net present value of complete elimination of pH-related yield losses would justify expenditure of \$7660 ha^{-1} (\$3100 A^{-1}), based on a 5% interest rate amortized over 20 yr. This value exceeds the cost of the elemental sulfur that would be required to neutralize all the $CaCO_3$ in the 0- to 15-cm (0- to 6-in) soil profile. While the economics of amelioration of high-pH soils appear potentially favorable, economic viability will depend on efficacy of S^0 applications in reducing pH and improving crop yield. Data from this experiment will, over time, provide data for support of economic decision-making.

SUMMARY AND CONCLUSIONS

Initial results of this research confirm the potential for use of elemental sulfur to ameliorate high pH, calcareous soils in higher rainfall areas of the eastern prairie pothole region of the North-Central United States. Economic viability of this practice will depend on yield impacts related to pH reduction and potential salt accumulation and prices for crops, land, and elemental sulfur. This experiment will continue to be monitored through future years for sulfur treatment effects on crop yield, soil pH, and soil EC. This data will in turn be used as a basis for analysis of the economic viability of elemental sulfur applications.

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Fig. 7-1. Deliniation of the prairie pothole region of the North-Central United States.

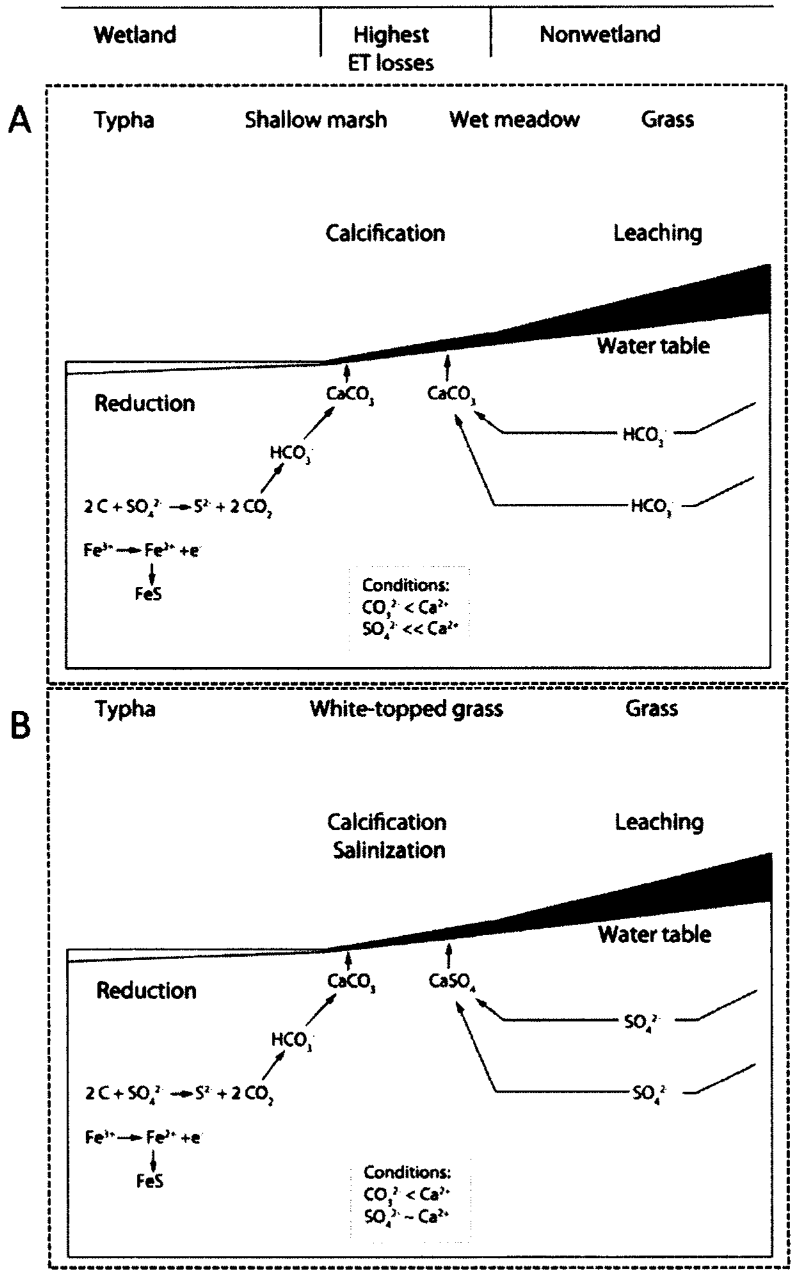

Fig. 7-2. Biogeochemistry of wetland edges in the more humid portions of the prairie pothole region. Soil calcium concentrations generally exceed carbonate concentrations in this region. When calcium concentrations exceed sulfate concentrations (A), dissolved bicarbonate ions move from both wetland and nonwetland portions of the landscape to the wetland edge, where evapotranspiration is highest. Soil water becomes supersaturated with respect to bicarbonate, and bicarbonate precipitates with calcium as calcite. When calcium concentrations approximately equal sulfate concentrations (B), sulfate is leached from uplands, resulting in precipitation of both calcite and gypsum at the wetland edge.

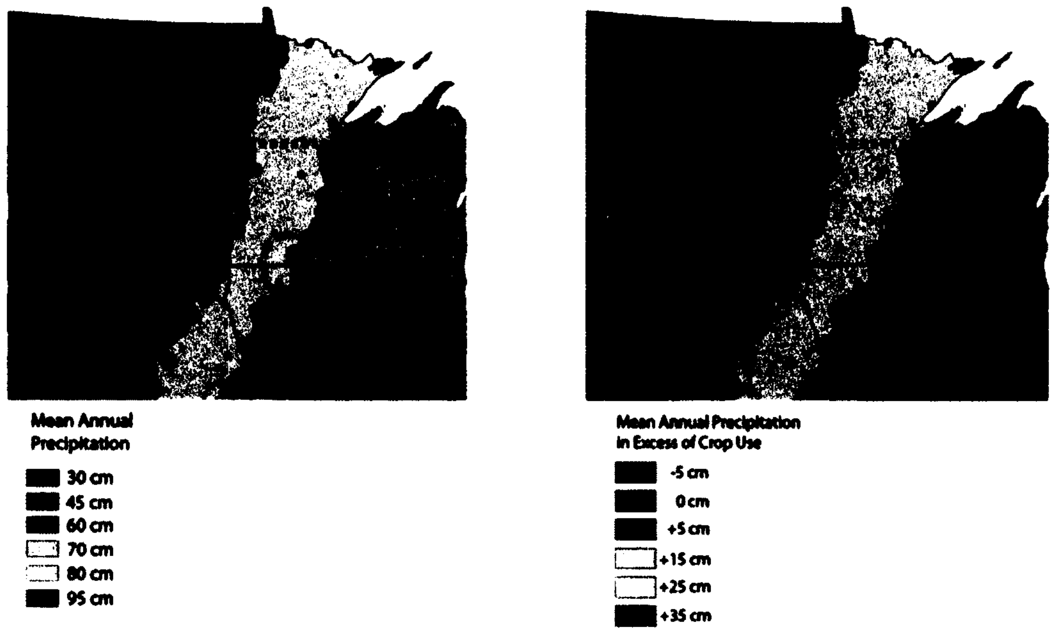

Fig. 7-3. Mean annual precipitation in the prairie pothole region (left panel) and mean annual precipitation in excess of crop evapotranspiration (right panel). Excess precipitation and leaching potential increase substantially from west to east in the prairie pothole region.

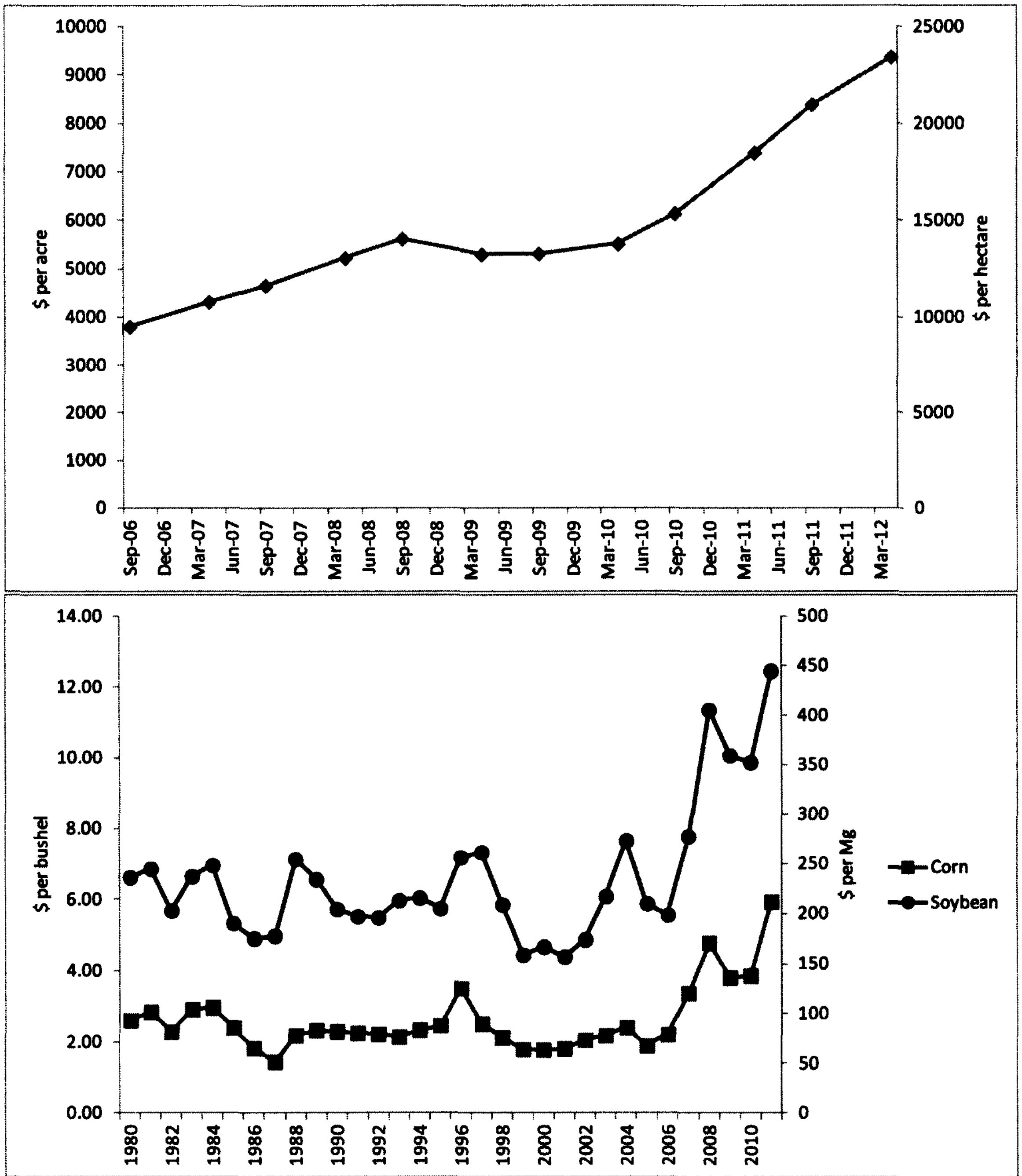

Fig. 7-4. Mean semiannual farmland sales price in Iowa for 2006-present (top panel; Realtor's Land Institute, 2012) and mean annual prices received for crops in Iowa 1980-present (bottom panel; Johanns, 2012).

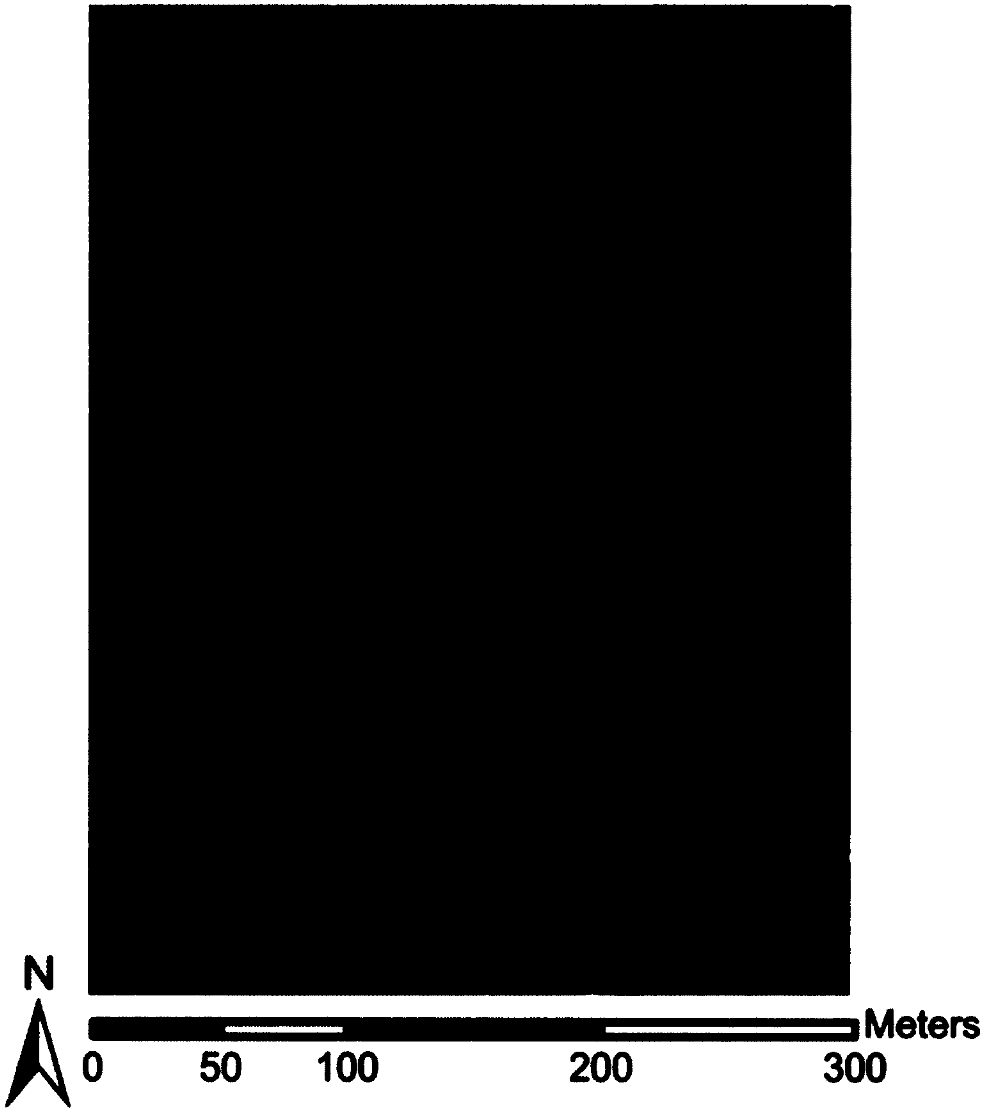

Fig. 7-5. Schematic of experimental area showing treatments of elemental sulfur (1200 kg ha^{-1} S^0; 1071 lb A^{-1}) and controls (yellow) imposed on USDA-NRCS soil map (orange) and aerial photo. White areas of aerial photo indicate calcite accumulation at soil surface.

Table 7-1. Estimates of economics of crop losses associated with high soil pH in the prairie pothole region in years 2000 and 2010. Metric units are presented in upper portion; English units are presented in lower portion.

Year	2000	2010
Expected corn yield (kg ha^{-1})	10,000	11,300
Average pH-related yield loss (kg ha^{-1})	2,500	2,800
Corn price ($ Mg^{-1})	70.04	233.35
Economic loss ($ ha^{-1})	175.86	659.12
Expected soybean yield (kg ha^{-1})	2,700	3,000
Average pH-related yield loss (kg ha^{-1})	1,075	1,200
Soybean price ($ Mg^{-1})	171.54	457.33
Economic loss ($ ha^{-1})	184.56	553.53
Economic loss over 2-yr rotation ($ ha^{-1})	360.42	1212.65
Expected corn yield (bu A^{-1})	160	180
Average pH-related yield loss (bu A^{-1})	40	45
Corn price ($ bu^{-1})	1.78	5.93
Economic loss ($ A^{-1})	71.20	266.85
Expected soybean yield (bu A^{-1})	40	45
Average pH-related yield loss (bu A^{-1})	16	18
Soybean price ($ bu^{-1})	4.67	12.45
Economic loss ($ A^{-1})	74.72	224.10
Economic loss over 2-yr rotation ($ A^{-1})	145.92	490.95

Table 7-2. Soil pH, sulfate S, electrical conductivity (EC), and soybean seed yield as affected by elemental sulfur treatment.

Sulfur rate	df	pH	SO_4-S	EC	Soybean yield	
kg ha^{-1}			mg kg^{-1} (ppm)	mmhos cm^{-1}	Mg ha^{-1}	bu A^{-1}
0		7.83a†	9a	0.55a	1.482a	22.06a
1200		7.59b	33b	0.90b	1.433a	21.33a
			ANOVA			
Source of variation						
Sulfur rate	1	***	***	***	ns	

*** Significant at the 0.001 probability level.
† Within columns, means followed by the same letter are not significantly different according to LSD (0.05)

Table 7-3. Economics of elemental sulfur for amelioration of high-pH calcareous soils in the North-Central United States.

Elemental Sulfur Cost		Annual Cost†		Break-even reduction in pH-related
—$ ha^{-1}$–	—$ A^{-1}$—	—$ ha^{-1}$–	—$ A^{-1}$—	————%————
250	101	20	8	3
500	202	40	16	6
750	304	60	24	10
1000	405	80	32	13

†Annual cost is calculated by amortizing the elemental sulfur cost over 20 yr at a 5% interest rate.

‡Break-even reduction in yield loss is calculated by dividing annual cost by 606.33 $ ha^{-1} (245.45 $ A^{-1}), which is the annualized expected economic crop loss associated with high-pH soils in 2010 (Table 7-1).

GENERAL CONCLUSIONS

The core question behind every decision faced by a farmer is: How do I make the best use of limited resources? In the coming decades, agricultural sustainability will depend on the ability of farmers to make increasingly accurate and precise decisions to optimize resource allocation. Global demand for food is projected to double by 2050 (Tilman et al., 2011). This demand will only be met through more productive use of existing resources.

In the United States, research by land-grant universities has provided the foundation for recommendations on optimum fertilizer use. These recommendations typically call for uniform rates of nutrients over state-wide or regional scales for certain crops and rotations, and are based on mean responses over multiple years and locations. While such recommendations have provided valuable guidance, they do not account for the intrinsic spatial and temporal variability in crop demand and soil nutrient supply. Consequently, uniform fertilizer applications result in some areas of fields receiving more nutrients than necessary, while other areas are underfertilized. Such errors or misapplication of nutrients often lead to combined problems of less than optimum yield in some parts of the field and excess fertilization in other parts of the field, problems that may result in economic loss to farmers and eutrophication of water ways into which fields drain.

By quantifying the variability in soil nutrient behavior and crop response over space and time, this work showed that such spatial variability in nutrient cycling is significant to agronomic decision-making. By accurately and precisely tailoring agronomic inputs to the landscape, site-specific management practices can enhance economic returns to farmers, make more efficient use of scarce resources, and reduce negative environmental effects.

We observed spatial variability in (1) crop removals of soil phosphorus, (2) soil phosphorus buffering capacity, (3) soil nitrogen cycling, and (4) corn and soybean yield response to nitrogen, phosphorus, and zinc.

We showed that grain phosphorus content is significantly related to soil test phosphorus levels, grain yield, and fertilizer phosphorus rates. Our results indicated that actual grain phosphorus content is lower than current regional guidelines, with greatest divergence at low yield levels and low soil test phosphorus levels. By improving accuracy of grain phosphorus content estimates and including spatially explicit data as predictors of grain phosphorus content, agronomists will be able to estimate spatial variability in mass-balance of soil phosphorus and refine fertilizer estimates to more precisely meet crop phosphorus needs (Mallarino, 2009).

We found substantial within-field variation in soil phosphorus buffering capacity. Buffering capacity exhibited spatial correlation over distances of ≈100 m, indicating that variability in buffering capacity is not random across fields, but is a pronounced spatial feature. Quantities of net phosphorus addition required per unit increase in soil test phosphorus level varied by up to 350%. This variability was highly correlated with soil pH, with greatest buffering capacity observed in the highest pH soils. Accounting for variability in phosphorus buffering capacity when making fertilizer phosphorus rate decisions will provide economic benefits by allowing farmers to most rapidly attain the most profitable soil test phosphorus level (Lowenburg-DeBoer and Reetz, 2002) and reduce environmental impacts associated with unintended soil phosphorus variability (Mallarino et al., 2001).

Our results showed temporal consistency in the spatial patterns of soil nitrogen mineralization tests, indicating the relevance of results from a single sampling over multi-year time frames and showing that these tests might serve as the basis for spatially-variable fertilizer nitrogen applications for multiple years. Like phosphorus buffering, these patterns exhibited clear spatial structure at scales suitable for management with agricultural equipment. The relationship between patterns of potentially mineralizable nitrogen and soil nitrate levels was dependent on uniformity of soil drainage. Variability in physical conditions for nitrogen mineralization must also be taken into account when attempting to predict the quantity of soil nitrogen available to crops.

Soybean yield was greatly influenced by soil test phosphorus and zinc levels in this 6-yr experiment. In moderately acidic and neutral soils, economic optimum soil test phosphorus levels were ≈15 mg kg^{-1}, similar to current recommendations (Rehm et al., 2001; Sawyer et al., 2008). However, in moderately alkaline soils, economic optimum soil test phosphorus levels were ≈30 mg kg^{-1}. Similarly, economic optimum soil test zinc levels were substantially higher in moderately alkaline soils. Of soil chemical parameters, soybean yield related most consistently to soil pH, with yield exhibiting strong inverse relationship to pH.

Coru yield was significantly affected by nitrogen and phosphorus fertilizer rates and their interactions. In all six site-years of this experiment, highest corn yields were associated with the highest rate combinations of nitrogen and phosphorus fertilizer. In three of six site-years, application of 56 kg ha^{-1} fertilizer P resulted in significant increases in economic optimum nitrogen rate. Synergistic interactions between nitrogen and phosphorus fertilizers are currently not considered in fertilizer rate recommendations. This work indicates that such interactions could significantly alter economic optimum rates.

Soybean quality components exhibited consistent behavior between sites within years, but inconsistent behavior across years, indicating the significance of regional climate variability in regulating soybean quality. Corn quality responded consistently to nitrogen fertilizer. Nitrogen rate was positively related to corn protein concentration and negatively related to corn starch concentration.

Application of a nitrogen-phosphorus-sulfur-zinc starter fertilizer to corn and soybean significantly increased mean corn yield, but did not significantly affect overall mean soybean yield. For corn, greatest responses were observed in treatments receiving the highest rates of nitrogen and phosphorus fertilizer. For soybean, positive responses to starter were observed in areas of the field where soil test phosphorus levels were deficient. Results suggest that site-specific starter fertilizer applications could be more efficient than uniform, whole-field applications.

Of all soil variables, pH exhibited dominant control over many of the responses we studied on these calcareous glacial till soils. Economic analysis indicated that effective amelioration of high pH soils would justify investment of 7660 \$ ha^{-1}. Preliminary investigation suggests that elemental sulfur may effectively lower soil pH if excess precipitation is sufficient to leach dissolved salts from the upper soil profile.

In addition, we suggest three areas of research to assist site-specific agronomic management. First, we recommend development of a soil phosphorus buffering capacity test that could be conducted alongside routine phosphorus availability analysis. Such a test would allow more efficient tailoring of phosphorus fertilizer rates to achieve optimum soil phosphorus levels. Second, we recommend more extensive analysis of within-field variability in optimum soil phosphorus levels. Third, we recommend more extensive analysis of nitrogen-phosphorus fertilizer interactions, including their effects both on corn yield and on economic optimum rates.

The relationships observed in this research include only a small subset of potential crop-nutrient interactions. The complexities of these relationships and implications for management make the simplicity of uniform fertilizer rate recommendations to appear appealing. However, the potential economic and productivity gains from accounting for such variability will make site-specific management essential to meeting needs for food in the future.

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